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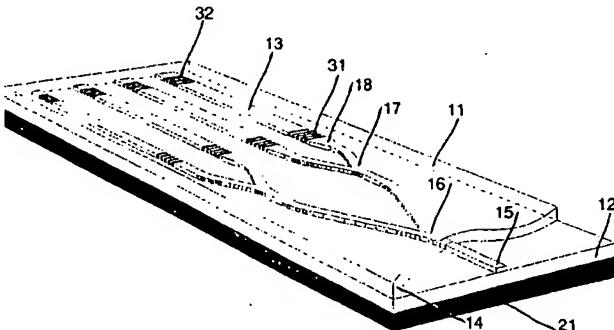
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(54) Title: MULTI-WAVELENGTH LASER SYSTEM



**WO 01/22542 A2** (57) Abstract: The present invention relates to a system and a method providing multi-wavelength emitting optical integrated planar waveguide device with large wavelength span, having tight control over absolute and especially relative positions of the emitted wavelengths, as well as narrow line widths. The  $n_{eff}$  experienced by a laser mode in a waveguide is at least partly determined by the physical overlap, the confinement factor, between the laser mode and the refractive index profile of the waveguide core. If the waveguides have well defined refractive index profiles, adjusting the transverse dimensions of the waveguide core adjusts the refractive index profile, and thus the confinement factor and  $n_{eff}$ . According to the present invention, two or more waveguide lasers are formed wherein the reflective members forming the laser cavity have a spectrally dependent reflectivity which depends upon the effective refractive index,  $n_{eff}$ , experienced by a laser mode at the position of the reflective member. By identical reflective members, such as Bragg gratings, for the different lasers, the wavelength of the lasers can be adjusted by adjusting the relative transverse dimensions, such as the widths, of the lasers. This allows for a precise relative tuning of the lasers, and eliminates uncertainties in the relative grating periods of the Bragg gratings. The dependence of  $n_{eff}$  upon the width  $w$ ,  $n_{eff}(w)$ , are preferably large in order to span a large range of wavelength using only a small variation in the width of the waveguides. Thereby different lasers will have approximately the same dimensions.

**MULTI - WAVELENGTH LASER SYSTEM**

The present invention relates to a system and a method providing multi-wavelength emitting optical integrated planar waveguide device with large wavelength span, having

- 5 tight control over absolute and especially relative positions of the emitted wavelengths, as well as narrow line widths.

Since the onset of interest in the research area known as Integrated Optics, the aim of research has been towards fabricating highly functional optical integrated circuits (OIC's)

- 10 with a high level of integration of state-of-the art components.

A vast number of different materials systems and technologies are used for the fabrication of these OIC's. Typically used technologies for OIC's are based either on glass-, polymer- or semiconductor materials, each of these technologies having pros and cons. However,

- 15 common to all OIC's is the ability to produce and/or manipulate light signals, which typically are launched into an optical fibre either for telecommunication purposes, test-measurement- or sensor applications.

Within optical telecommunication, OIC's such as dense wavelength division multiplexers

- 20 (DWDM's) and optical add/drop multiplexers are expected to play an increasing role in the future as more and more standard ITU (International Telecommunication Union) channels are transmitted through single fibres. The spacing of ITU channels varies when technology evolves making it possible to have more channels within less wavelength span. At the time, standard minimum ITU channel spacing is 100GHz or 50GHz. These
- 25 components perform operations on the transmitted signals that would otherwise be very hard to achieve using an all-fibre solution. Furthermore, the OIC's are likely to be smaller, cheaper and more stable than bulk optics solutions. Other uses for OIC's include e.g. small gyroscopes and electrical field sensors.

- 30 For telecommunication-, measurement-, and sensor-applications, the light sources typically used are lasers, as these emit at definite wavelengths with narrow line widths, making it possible to transmit more standard ITU channels through a fibre, or to make more precise measurements. Furthermore, the coherence and phase of the laser light is extensively used in as well telecommunication as in several OIC's such as ring resonators

and Mach-Zehnder switches. Thus, there is a promising market for lasers, and especially multi-wavelength lasers.

To fully exploit the transmission possibilities of the fibres and the OIC's, a conglomerate of 5 individual lasers each emitting at a specific wavelength is required, which will be an expensive as well as a bulky solution. Therefore, an integrated optical device emitting at multiple definite wavelengths that can be individually modulated is likely to be highly attractive as light source in high bit-rate DWDM networks. For testing of OIC's for DWDM networks, and the networks themselves a simple integrated optical device without 10 modulators emitting at a range of wavelengths on the ITU communication grid will prove to be very useful.

Such multi-wavelength emitting laser devices need to possess certain qualities for them to qualify as sources in the above-mentioned applications, such as temperature- and 15 channel stability, narrow line widths as well as single-mode and single polarisation operation.

Besides these qualities it will be advantageous if the multi-wavelength emitting devices can be fabricated in a technology, which facilitates good interfacing to the optical fibres. 20 Matching the fibre and the device material systems ensures optimal coupling of the optical signal from the device to the fibre and vice versa.

Multi-wavelength emitting devices have been fabricated in the past, in a number of different technologies.

25

One way to come about such a device is by splicing together a number of separate fibre lasers, each emitting at a predetermined wavelength. Such a solution facilitates excellent coupling of light from the laser structure to fibre networks. Furthermore, this method provides easy amplification of the laser signals around 1550 nm by using the non- 30 absorbed pump light to pump an erbium doped fibre amplifier in conjunction with the lasers.

J. Hübner et al. "Five wavelength DFB fibre laser source for WDM systems", Electronics Letters, Vol. 33, No. 2, January 1997, pp. 139 – 140, discloses a five wavelength fibre 35 laser source. The disclosed method consists of fabricating five separate lasers in erbium

doped fibres, and subsequently splicing together the separate fibre lasers into one multi-wavelength emitting device. The individual lasers show a peak power of 150 µW and a line width of less than 15 kHz when pumped by 60 mW of 1480 nm light. Using this approach, the authors achieved polarisation and longitudinal single mode operation of the 5 lasers.

Using UV-exposure and a single phasemask to inscribe the Bragg gratings into the cores of the fibres, J. Hübner *et al.* achieved varying Bragg laser wavelengths by applying stress to the fibres during Bragg grating fabrication. When no stress is applied to the fibre during 10 grating inscription, the resulting Bragg wavelength is given by the phasemask period (assuming the laser is operated without applied stress). On the other hand, if the fibre is stretched during grating inscription the effective inscribed grating period will decrease when the stress is released, hence decreasing the wavelength at which the grating will reflect. This technique allows the authors a tuning range of approximately 5 nm, with a 15 reproducibility of around 0.2 nm.

Multi-wavelength emitting devices can also be fabricated in semiconductor materials, where passive and active sections can be made, making it possible to form passive waveguides as well as lasers in the active regions. Distributed feedback (DFB) lasers can 20 be formed in the active regions, with direct injection into passive waveguides. Tailoring the passive waveguide structure to multiplex the signals from the separate lasers into a single waveguide facilitates easy coupling of the output wavelengths into a fibre. Modulation of the laser outputs becomes very easy as the lasers are modulated by the current sources. Furthermore, due to the high refractive index contrast typically experienced in such 25 semiconductor structures the size of such a structure can be made particularly small.

K. Aiki *et al.* "Frequency multiplexing light source with monolithically integrated distributed-feedback diode lasers", Appl. Phys. Lett., Vol. 29, No. 8, October 1976, pp. 506 – 508, discloses a method of fabricating an array of six GaAs-GaAlAs DFB diode lasers, 30 multiplexed into one output waveguide. Liquid-phase epitaxy (LPE) was used to successively grow differently doped layers, forming an active sandwich structure where the lasers were to be fabricated. Six third order gratings with varying period were subsequently made one at a time on the surface, using a holographic exposure setup with a sliding slit, and subsequent chemical etching. Following the grating formation, all except 35 the grating regions were completely etched away down to the substrate, and passive

GaAlAs layers were regrown using LPE, followed by the formation of a passive waveguide structure, multiplexing the separate laser outputs into one waveguide.

This fabrication method allowed the authors to obtain a laser wavelength separation of 2  
5 nm ± 0.5 nm around approximately 864 nm, and a spectral width of the lasers of approximately 0.03 nm. Due to the abrupt transition from the lasers to the passive waveguides a very low coupling efficiency of approximately 30% was obtained, contributing to an over-all quantum efficiency as measured at the terminal of approximately 0.3%.

10

In order to reduce the coupling loss and back reflection from the interface between a multi-wavelength emitting device and fibre the multi-wavelength emitting device should be made in a fibre compatible material regarding refractive index, e.g., silica. Furthermore, the refractive index profile of the waveguides and hence the mode profile should be fibre  
15 compatible.

D. L. Veasey *et al.* "Arrays of distributed-Bragg-reflector waveguide lasers at 1536 nm in Yb/Er codoped phosphate glass", *Appl. Phys. Lett.*, Vol. 74, No. 6, February 1999, pp. 789 – 791, discloses a method of fabricating an array of integrated waveguide lasers in a  
20 phosphate glass substrate. The waveguides were formed by K<sup>+</sup>/Na<sup>+</sup> ion exchange in an Erbium/Ytterbium co-doped phosphate glass, using 3 – 8 µm wide line apertures. The DBR structure was formed using a thin highly reflective dielectric mirror on the pump input facet, and a surface relief Bragg grating in the other end. This Bragg grating is initially  
formed in a thin layer of photoresist using a holographic exposure setup, and  
25 development. Covering the top of the developed photoresist structure with chromium, the photoresist structure is transformed into the surface of the waveguides using reactive ion etching.

This approach allowed the authors to obtain lasers with stable longitudinal single mode  
30 operation, line widths less than 500 kHz, and output powers of 80 mW. By varying the aperture widths from 5 µm to 8 µm and measuring the position of the corresponding laser wavelengths it was found that the wavelength span ranged from approximately 1536.0 nm at 5 µm width, to approximately 1536.3 nm at 8 µm width. The wavelength span of approximately 0.3 nm over 3 µm of wavelength width, corresponds to less than 50 GHz,  
35 which compares to the spacing between two adjacent ITU channels.

Kitagawa *et al.* "Single frequency Er<sup>3+</sup>-doped silica-based planar waveguide laser with integrated photo-imprinted Bragg reflectors", *Electronic Letters*, Vol 30, No. 16, pp. 1311 - 1312, August 1994, relates to two identical planar waveguide lasers, formed in doped 5 silica glass. The lasers are formed by making waveguide cores of Er<sup>3+</sup>-doped silica, embedded in silica claddings. The waveguide cores has dimensions 8 x 7 µm and are formed using standard deposition and etching techniques. Using UV writing through a phase mask, two spatially separated Bragg gratings are induced in the core, forming a DBR laser cavity. Single frequency (or mode) operation with an output of 340 µW is 10 obtained at 1546 nm, for pump powers less than 300 mW. The presented lasers emit at the same single wavelength and do therefore not apply as a multi-wavelength emitting device source for IOC uses. The reference contains no possibilities for varying the laser wavelength of the lasers. Moreover, the geometrical parameters of the waveguide are considered unfavourable. An 8 x 7 µm cross section area will typically support several 15 transverse modes.

Single mode waveguides are required in order to obtain efficient transmission in waveguides and fibres, as well as good coupling from waveguides to fibres. Also, the combination of the waveguide cross section dimensions and the refractive index step 20 should be optimised to ensure optimum mode overlap between the signal mode at 15xx nm (28 ≤ xx ≤ 68), and the pump mode at 980 nm, alternatively 1480 nm. This helps optimising gain in the active medium.

Having a multi-wavelength emitting device formed as a series of spliced DFB fibre lasers 25 is disadvantageous, since an isolator is often needed in between each of the lasers, thus increasing cost and complexity. Furthermore, the number of cascaded lasers is limited by the requirement of uniform output power at the different laser wavelengths. Due to pump power absorption in the lasers and the isolators, the output power from the lasers further down the line will decrease, ultimately limiting the number of lasers to a maximum of 30 approximately eight lasers.

It is another disadvantage of multi-wavelength emitting device formed as a series of spliced DFB fibre lasers, that each laser is fabricated individually. This introduces some uncertainties in the relative laser frequencies of a series of lasers.

It is a disadvantage of multi-wavelength emitting devices formed in semiconductor materials that the index of refraction of these materials is much higher than the refractive index of silica fibres, giving rise to very high coupling losses as well as back reflections, which might disturb the stability of the lasers.

5

The method of using phosphate glass for multi-wavelength emitting devices poses a number of disadvantages:

While the refractive index of a typical phosphate glass is considerably smaller than that of  
10 semiconductor materials, it is still somewhat larger than that of standard silica fibres, thus giving rise to coupling loss and back reflections which also might disturb the stability of the lasers.

There is a reduction of the wavelength span originating from the phosphate glass host,  
15 which effectively prevents amplification above approximately 1544 nm. This low upper-limit for amplification excludes a very large range of ITU channels, thereby significantly limiting the applicability of such devices.

Furthermore, the only possibility of varying the laser wavelengths considerably in order to  
20 cover a large span of ITU channels is to vary the physical grating period, which increases the complexity and cost of the device.

In the device of D. L. Veasey *et al.*, the very small span of approximately 0.3 nm is most likely due to the nature of the graded refractive index profile obtained in the ion exchange  
25 process.

Another disadvantage of the device of D. L. Veasey *et al.* is, that DBR lasers, fabricated using the presented method are prone to be easily affected by external influences, as the grating and the waveguides are directly accessible on the upper surface of the device.

30

#### SUMMARY OF THE INVENTION

It is an object of the present invention to provide a multi-wavelength emitting laser device wherein it is possible to span several standard ITU channels by varying the transverse dimensions of waveguides having the same grating period.

35

It is another object of the present invention to provide a multi-wavelength emitting laser device where Bragg gratings can be imprinted with a single exposure session using coherent actinic radiation. Thus, Bragg gratings can be made simultaneously in several waveguide cores, which gives a high degree of precision, making it possible to precisely  
5 control the position of the emitted wavelengths.

It is a further object of the present invention to provide a multi-wavelength emitting laser device in which the Bragg gratings are UV written. This allows for a fine-tuning of the emitted wavelengths in a post-processing step using a focused beam of actinic radiation  
10 and scanning the previously fabricated Bragg gratings.

It is a still further object of the present invention to provide a multi-wavelength emitting laser device where the macroscopic variations in the silica layers across the substrate, and macroscopic variations in the photolithography and etching steps, can be neglected  
15 since the lasers are placed in close proximity.

It is a still further object of the present invention to provide a multi-wavelength emitting laser device that eliminates local temperature fluctuations from external influences by employing silicon as a substrate, which has thermal conductivity two orders of magnitude  
20 larger than silica. This ensures consistent laser channel spacing.

It is a still further object of the present invention to provide a multi-wavelength emitting laser device having a high mechanical stability, achieved by the high out-of-plane bending stiffness property of the silicon substrate.

25

According to the present invention, the above-mentioned objects are complied with by providing waveguide lasers having a well-defined refractive index profile. At any cross section of the laser cavity, the overlap between the index profile and a transverse mode of a laser mode at least partly determines the effective refractive index  $n_{\text{eff}}$  experienced by  
30 the laser mode. The index profile is typically determined by the shape of the waveguide core surrounded by a cladding. Hence, according to the present invention, by providing a well-defined index profile, a change in one of the transverse dimensions of the waveguide core will give rise to a large change in the overlap between the index profile and a transverse mode of the radiation. Thus, the variation of the transverse dimensions of the  
35 waveguide core translates directly into a substantial variation of the effective refractive

index,  $n_{\text{eff}}$ , as experienced by laser modes of interest. Throughout the present description and claims, the cross-sectional or transverse dimensions of the waveguide core, such as its width or height, will be referred to as the width of the waveguide core since it preferably is the width, which is varied.

5

The overlap between a mode of the electromagnetic field and the waveguide core depends on the index profile  $n(x,y)$ . A measure of the mode overlap can be found by defining a *confinement factor*,  $\eta$ , as

$$\eta = \frac{\int \int_{x,y=-\infty}^{x,y=+\infty} n(x,y)v(x,y)dx dy}{\int \int_{x,y=-\infty}^{x,y=+\infty} n(x,y)n(x,y)dx dy},$$

10 where  $v(x,y)$  is the modal distribution of the electromagnetic field. The confinement factor hence expresses the degree to which the mode of the electrical field is confined within the waveguide core. (Ladouceur and Love: "Silica-based Buried Channel Waveguides and Devices", Chapman & Hall, London 1996 and Sales and Teich: "Fundamentals of Photonics", Wiley & Sons, New York 1991)

15

For highly confined modes the confinement factor has a value close to 1 (unity) while the value approaches 0 (zero) in the case of very weakly confined modes. This corresponds to situations where the effective refractive index  $n_{\text{eff}}$  approaches the refractive index of the core ( $\eta \approx 1$ ) and the refractive index of the cladding ( $\eta \approx 0$ ), respectively. The confinement  
20 factor is influenced by the index difference between the core and the cladding, as well as the detailed shape of the index profile  $n(x,y)$ . According to the present invention, the confinement factors of the waveguides used, depends strongly on the width of the waveguide. Such a situation can typically be found in waveguides where the index profile changes abruptly between core and cladding (step-like index profile). However,  
25 depending on various parameters such as the specific waveguide design, materials, method of fabrication and the laser mode, a number of different index profiles may give favourable confinement factors, where  $d\eta/dw$  lies within a desired interval.

Regarding planar waveguide lasers, it is important to be aware of the distinction of a  
30 single mode waveguide laser and a single mode waveguide. Single mode waveguide laser relates to a single longitudinal and single transversal laser mode and hence to the wavelength spectrum as in the normal terminology. Single mode waveguide, however,

relates to the transverse spatial modes supported by the waveguide, since a waveguide as such does not support discrete longitudinal modes.

The wavelength of a laser is typically determined by the spectrum of the gain medium and  
5 the spectrally dependent reflectivity of one or more reflective members establishing the laser cavity. Often a reflective member with a spectrally narrow reflectivity at a well-defined wavelength is used to fine tune the laser wavelength. The spectrally dependent reflectivity of a reflective member may depend upon the effective refractive index at the position of the reflective member, and according to the present invention, adjusting the  
10 core width will adjust the laser wavelength.

Thus, in a first aspect, the present invention provides a laser system comprising a first and a second laser,

15 the first laser comprising:

- a first substrate holding a first waveguide structure, said first waveguide structure having a core and a cladding region, wherein the core region comprises an active region holding one or more dopants,
- a first and a second reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the laser cavity supports a first laser mode, said first laser mode experiencing a first effective refractive index,  $n_{eff1}$ , at the position of the first reflective member, and wherein the core region has a width,  $w_1$ , at the position of the first reflective member,

25 the second laser comprising:

- a second substrate holding a second waveguide structure, said second waveguide structure having a core and a cladding region, wherein the core region comprises an active region holding one or more dopants,
- a third and a fourth reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the laser cavity supports a second laser mode, said second laser mode experiencing a second effective refractive index,  $n_{eff2}$ , at the position of the third reflective member, and wherein the core region has a width,  $w_2$ , at the position of the third reflective member,

the laser system being characterised in that  $n_{\text{eff}1}$  is different from  $n_{\text{eff}2}$  and that the first and second waveguide structures are adapted to provide, at the positions of the first and third reflective members, a dependency of the effective refractive indices upon the core widths,  $n_{\text{eff}1}(w_1)$  and  $n_{\text{eff}2}(w_2)$ , satisfying  $dn_{\text{eff}1}/dw_1 > 2 \times 10^{-4} \mu\text{m}^{-1}$  and  $dn_{\text{eff}2}/dw_2 > 2 \times 10^{-4} \mu\text{m}^{-1}$ .

5

For a waveguide in a standard cartesian right-hand co-ordinate system (x,y,z), having propagation direction along the z-axis, the refractive index distribution in the plane normal to the direction of propagation  $n(x,y)$  determines the mode profile of the optical field.

Given  $n(x,y)$ , the distribution of the electromagnetic field can be calculated from Maxwell's 10 equations using a variety of numerical methods well-known from the literature, such as the finite difference- or finite element methods. Varying  $n(x,y)$ , for example by varying the waveguide width, makes it possible to calculate the influence of the width on the mode overlap with the waveguide core, or alternatively the effective refractive index variation. Thus,  $dn_{\text{eff}}/dw$  (where dw is the differential variation of the width, and  $dn_{\text{eff}}$  is the 15 corresponding differential variation in the effective refractive index) can be calculated. In this way, a refractive index distribution or profile,  $n(x,y)$ , that yields a response  $dn_{\text{eff}}/dw$  in a desired interval can be determined.

Having fabricated an array of closely spaced waveguides of varying width, the 20 corresponding experimental curve  $\Delta n_{\text{eff},i,i+1}/\Delta w_{i,i+1}$ , where i is an arbitrary waveguide in the array, can be measured for example by creating Bragg gratings in the waveguides and measure the corresponding Bragg wavelength which is directly proportional to the effective refractive index. Another way to determine the  $\Delta n_{\text{eff},i,i+1}/\Delta w_{i,i+1}$  curve is through the use of SNOM (Scanning Nearfield Optical Microscopy). This technique can be used to 25 obtain the  $n(x,y)$  distribution which then can be fed into a finite difference calculation scheme that gives the effective refractive index.

According to a second aspect, the present invention provides a laser system comprising a first and a second laser,

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the first laser comprising:

- a first substrate holding a silica-based first waveguide structure, said first waveguide structure having a core and a cladding region, wherein the core region comprises an 35 active region holding one or more dopants,

- a first and a second reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the first waveguide structure has a first core width,  $w_1$ , at the position of the first reflective member, and, wherein the laser cavity supports a first laser mode, said first laser mode experiencing a first effective refractive index,  $n_{\text{eff}1}$ , at the position of the first reflective member, wherein  $n_{\text{eff}1}$  is associated with a first refractive index profile, and

the second laser comprising:

10

- a second substrate holding a silica-based second waveguide structure, said second waveguide structure having a core and a cladding , wherein the core region comprises an active region holding one or more dopants, and

15

- a third and a fourth reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the second waveguide structure has a second core width,  $w_2$ , at the position of the third reflective member, and, wherein the laser cavity supports a second laser mode, said second laser mode experiencing a second effective refractive index,  $n_{\text{eff}2}$ , at the position of the third reflective member, wherein  $n_{\text{eff}2}$  is associated with a second refractive index profile,

characterised in that  $n_{\text{eff}1}$  is different from  $n_{\text{eff}2}$ ,  $w_1$  is different from  $w_2$ , and that  $\frac{n_{\text{eff}2} - n_{\text{eff}1}}{w_2 - w_1}$  is larger than  $2 \times 10^{-4} \mu\text{m}^{-1}$ .

25 Typically, a predetermined difference,  $n_{\text{eff}2} - n_{\text{eff}1}$ , between the refractive indices is desired,

and hence the ratio  $\frac{n_{\text{eff}2} - n_{\text{eff}1}}{w_2 - w_1}$  expresses the change in the transverse dimensions of

the waveguide necessary to achieve this predetermined difference. By providing lasers with a large ratio, the present invention allow lasers to have desired differences between the refractive indices while having approximately the same dimensions.

30

According to both the first and the second aspect of the present invention, the effective refractive indices preferably determine the laser wavelength of the first and second laser. Hence, the variation of  $n_{\text{eff}}$  ensures that the lasers can be significantly detuned while

having similar dimensions. In order to achieve a large flexibility in the relative laser wavelengths,  $dn_{\text{eff}1}/dw_1$ ,  $dn_{\text{eff}2}/dw_2$  and  $\frac{n_{\text{eff}2} - n_{\text{eff}1}}{w_2 - w_1}$ , respectively, are preferably within the range  $2 \times 10^{-4} - 20 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $3 \times 10^{-4} - 15 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $4 \times 10^{-4} - 10 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $5 \times 10^{-4} - 8 \times 10^{-4} \mu\text{m}^{-1}$ ,

5 such as within the range  $6 \times 10^{-4} - 7 \times 10^{-4} \mu\text{m}^{-1}$ .

To achieve such large variations of  $n_{\text{eff}}$  in the width, it is essential to realise that the index profile must be well-defined and have a size and shape being commensurate to the size and shape of the transverse laser mode. The index profile should be adjusted so as to

10 make the confinement factor strongly dependent upon the transverse dimensions of the waveguide. Preferably, the waveguides of the first and second lasers have at least substantially the same index profile, meaning that  $n(x,y)$  have at least substantially the same shape whereas one is somewhat broader than the other due to the different widths.

15 In the prior art, the nature of the diffused index profiles of the waveguides give rise to a very low change of effective refractive index for different waveguide widths, and thus a very low laser wavelength span for practical waveguide widths.

The laser cavities in the system may be single-mode laser cavities emitting laser light at

20 well-defined centre frequencies. Preferably, the relative width of the first and second laser is adjusted so that the centre frequencies are separated by the interval 125 -1000 GHz, such as 75 -125 GHz, such as 37.5 - 62.5 GHz, such as 18.75 - 31.25 GHz, such as 9.375 -15.615 GHz, such as 7.5 -12.5 GHz, such as within the interval 1 - 7.5 GHz.

25 The centre frequencies of the light emitted from the laser cavities are preferably within the frequency range corresponding to wavelengths within the region from 500nm to 2000 nm, such as within the region 750nm to 900nm or 1300nm to 1650nm, preferably within the range 1528 - 1620 nm or 1300 - 1400 nm or 1000 - 1150 nm.

30 Preferably, the waveguides are glass based such as based on silica or other glass types. The substrates holding the lasers may be made of silicon, and the substrates may form part of the same silicon substrate. A cladding layer, or parts of such, separating the substrate and the waveguide core may be fabricated by thermally oxidising the silicon substrate.

In order for the waveguide cores to act as active regions, they are preferably doped with one or more dopants selected from the group consisting of: germanium, aluminium, phosphorous, erbium, neodymium and ytterbium.

5

A major advantage of the laser systems according to the first and second aspects of the present invention is that the waveguides forming the lasers can be positioned side by side in close proximity, even while the wavelengths are tuned by the waveguide dimensions.

The waveguide cores each define a centre axis, and preferably, the shortest distance

10 between those axis is larger than 10  $\mu\text{m}$ , such as larger than 50  $\mu\text{m}$  or 60  $\mu\text{m}$ , such as larger than 70  $\mu\text{m}$  or 80  $\mu\text{m}$ , preferably larger than 100  $\mu\text{m}$ , such as larger than 125  $\mu\text{m}$ , 150  $\mu\text{m}$  or 250  $\mu\text{m}$ .

The reflective members forming the cavities can be formed by refractive index

15 modulations in the core regions. These index modulations may define a substantially periodic grating structure in the core regions, possibly in the form of a Bragg grating. Typically, the grating period determines the spectrally dependent reflectivity of the grating and hence the laser wavelength. However, the grating period experienced by a laser mode depends on the effective refractive index experienced by the mode. Hence,

20 according to the present invention, gratings having the same physical grating period will provide different reflectivity when formed in waveguides having different widths. Thus, gratings with identical physical pitch can be formed in all lasers whereby the same mask can be used to define the grating for each laser. Thereby, the relative precision between the laser wavelengths is not influenced by the normal uncertainties of the relative

25 precision of different phase mask periods.

Preferably, the systems further comprises a light source for pumping the active region of the first and/or second laser, wherein said light source has a wavelength within the range of 930 - 990 nm, 1470 - 1490 nm or 750 - 850 nm. The power emitted from the pumped

30 laser cavities is preferably within the range 0.005 - 100 mW.

Alternatively, the above-mentioned objects are complied with by providing in a third aspect a single-mode laser emitting light around a centre wavelength,  $\lambda$ , said laser comprising

- a substrate holding a waveguide structure, said waveguide structure having a core and a cladding region, wherein the core region comprises an active region holding one or more dopants,

5 - a first and a second reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the core region has a width, w, at the position of the first reflective member,

the laser being characterised in that the waveguide structure is adapted to provide a dependency of the centre wavelength upon the core width, w, at the position of the first reflective member,  $\lambda(w)$ , satisfying  $d\lambda/dw \geq 0.2 \text{ nm}/\mu\text{m}$ . Again, in order to span a large range of wavelengths for applicable widths,  $d\lambda/dw$  is preferably within the range 0.2 - 2  $\text{nm}/\mu\text{m}$ , such as within the range 0.3 - 1.5  $\text{nm}/\mu\text{m}$ , such as within the range 0.4 - 1  $\text{nm}/\mu\text{m}$ , such as within the range 0.5 - 0.8  $\text{nm}/\mu\text{m}$ , such as within the range 0.6 - 0.7  $\text{nm}/\mu\text{m}$ .

15 The substrates holding the laser may be made of silicon. A cladding layer, or parts of such, separating the substrate and the waveguide core may be fabricated by thermally oxidising the silicon substrate.

20 In order for the waveguide core to act as an active region, it is preferably doped with one or more dopants selected from the group consisting of: germanium, erbium, aluminium, neodymium, and ytterbium. In a preferred embodiment, the active region consists of erbium co-doped Germanium-silica (germanosilicate), since the large gain bandwidth of this material allows for laser operation up to approximately 25 1620 nm.

The first and second reflective members forming the cavity may be formed by refractive index modulations in the core region. These index modulations may define a substantially periodic grating structure in the core region, possibly in the form of a Bragg grating.

30 Preferably, the laser cavity is pumped with a pump wavelength within the range of 930 - 990 nm, 1470 - 1490 nm or 750 - 850 nm, and will typically emit light with centre wavelength within range 1528 - 1620 nm or 1300 - 1400 nm or 1000 - 1150 nm. The power emitted from the laser cavity when pumped is preferably within the range 0.005 - 35 100 mW.

A plurality of single mode lasers as described above can be comprised in a multi-wavelength emitting device wherein the single-mode lasers have different widths at the positions of their first reflective members whereby each single-mode laser emit light with 5 different centre frequencies. The predetermined centre frequencies are preferably separated by predetermined frequency intervals such as by the interval 125 - 1000GHz or 75 - 125 GHz, such as 37,5 - 62,5 GHz, such as 18,75 - 31,25 GHz, such as 9,375 - 15,615 GHz, such as 7,5 - 12,5 GHz or 1 - 7,5 GHz.

- 10 As discussed previously, the refractive index profile is typically determined by the transverse dimensions, the width, of the waveguide core. However, the index profile may be modified using other methods such as irradiation with actinic radiation. Such modifications may be carried out in post-processing steps at selected parts of the waveguide structure.

15

The refractive index profile is preferably determined in the fabrication of a laser. Hence in a fourth aspect, the present invention provides a method of fabricating a laser according to the third aspect of the invention. Thus, in a fourth aspect, the present invention provides a method of fabricating a laser emitting light at a predetermined wavelength, said 20 method comprising the steps of:

forming a first waveguide structure having a core and a cladding region,

providing an active region within the core region, and

25

forming a first and a second reflective member in the core region so as to form a laser cavity with the active region, said laser cavity being adapted to support a laser mode, the core having a width w at the position of the first reflective member,

30 the method being characterised in that

at the position of the first reflective member, a refractive index profile of the waveguide structure is formed by adjusting the core width, w, so as to provide a predetermined spatial overlap with a profile of the laser mode so as to obtain the predetermined

35 wavelength of the laser mode.

The predetermined overlap at least partly determines an effective refractive index,  $n_{\text{eff}}$ , experienced by the laser mode at the position of the first reflective member, and the index profile is preferably adapted to provide, at the position of the first reflective member, a dependency of the effective refractive index upon the core width,  $n_{\text{eff}}(w)$ , satisfying

5  $\frac{dn_{\text{eff}}}{dw} > 2 \times 10^{-4} \mu\text{m}^{-1}$ .

Preferably, the reflective members are Bragg gratings, hence, the step of forming the first and second reflective members preferably comprises the step of forming the first reflective member by forming a Bragg grating in the core region. The Bragg grating may be a UV 10 written or a corrugated grating.

In a fifth aspect, the present invention provides a method of adjusting the relative wavelengths of two or more lasers, such as in a system according to the first or second aspect. Thus, in a fifth aspect, the present invention provides a method of adjusting 15 relative wavelengths of a first and a second laser, said method comprising the steps of:

providing the first laser comprising:

- a first substrate holding a first waveguide structure, said first waveguide structure having a core and a cladding region defining a refractive index profile for the first 20 waveguide structure, the core region comprising an active region holding one or more dopants,
- a first and a second reflective member each being formed in the core region so as to form a first laser cavity with the active region, said first laser cavity being adapted to support a first laser mode,

25

wherein, at the position of the first reflective member, a refractive index profile is formed by adjusting a core width,  $w_1$ , so as to provide a first predetermined spatial overlap with a profile of the first laser mode so as to obtain a predetermined first wavelength,  $\lambda_1$ , of the laser mode,

30

providing the second laser comprising:

- a second substrate holding a second waveguide structure, said second waveguide structure having a core and a cladding region defining a refractive index profile for the second waveguide structure, the core region comprising an active region holding one 35 or more dopants,

- a third and a fourth reflective member each being formed in the core region so as to form a second laser cavity with the active region, said second laser cavity being adapted to support a second laser mode,
- 5 where in, at the position of the third reflective member, a refractive index profile is formed by adjusting a core width,  $w_2$ , so as to provide a second predetermined spatial overlap with a profile of the second laser mode so as to obtain a predetermined second wavelength,  $\lambda_2$ , of the laser mode, and
- 10 adjusting the core widths  $w_1$  and  $w_2$  so as to provide a predetermined relation between the first and the second wavelength.

Preferably, the core widths  $w_1$  and  $w_2$  and the predetermined relation between the first and the second wavelength fulfil  $\frac{\lambda_2 - \lambda_1}{w_2 - w_1} \geq 0.2 \text{ nm}/\mu\text{m}$ , in order for the lasers to span a

- 15 large range of wavelengths for applicable widths. Optionally,  $\frac{\lambda_2 - \lambda_1}{w_2 - w_1}$  is within the range 0.2 - 2 nm/ $\mu\text{m}$ , such as within the range 0.3 - 1.5 nm/ $\mu\text{m}$ , such as within the range 0.4 - 1 nm/ $\mu\text{m}$ , such as within the range 0.5 - 0.8 nm/ $\mu\text{m}$ , such as within the range 0.6 - 0.7 nm/ $\mu\text{m}$ .
- 20 Preferably, at least the first and third reflective members are Bragg gratings, having at least substantially the same period, whereby the tuning of the wavelengths are primarily carried out by adjusting the width. Thereby, it is possible to apply the same mask when writing the different gratings, thereby eliminating any uncertainties in grating periods.

## 25 BRIEF DESCRIPTION OF THE FIGURES

Figure 1 shows a schematic view of an array of 6 buried waveguide lasers, made in a combination of doped and un-doped silica and placed on a silicon substrate. Approximately 12  $\mu\text{m}$  buffer glass separates the waveguide cores from the silicon substrate, and the surface of the top cladding. The individual waveguide lasers are spaced by 125  $\mu\text{m}$  centre-to-centre, and have increasing width. The laser resonator structures are defined by Bragg gratings imprinted directly into the waveguide cores, using a suitable phasemask (not shown), covering all the waveguides, and actinic radiation. The spatial positions of the Bragg gratings in the individual lasers are illustrated

by the alternating closely spaced light and dark areas in the waveguide cores in opposite ends. The dimensions are exaggerated for reasons of clarity.

Figure 2A (circle + arrow indicates which axis values should be read off) shows a Bragg wavelength as function of waveguide width,  $\lambda_B(w)$ . The curve 42 shows  $\lambda_B(w)$  for one polarisation, obtained for waveguides fabricated according to the present invention. For consistent fabrication process parameters this curve can be used to design laser structures according to Figure 1 having waveguide widths resulting in equidistantly spaced output laser wavelengths e.g. placed on the ITU grid. For comparison, a corresponding curve 41 shows measured laser wavelengths as function of waveguide width as obtained from Veasey et al.<sup>1</sup>. The two curves are shown on the same scale, with shifted vertical origins. Note the minute slope of the curve published in Veasey et al.

Figure 2B shows the effective refractive index as function of waveguide width,  $n_{\text{eff}}(w)$ , for the same cases as Figure 2A. Curve 44 is obtained for waveguides fabricated according to the present invention and corresponds to curve 42 of Figure 2A. Curve 43 is obtained from Veasey et al. and corresponds to curve 41 of Figure 2A.

Figure 3 shows a schematic view of an array of 4 buried planar waveguide lasers. The individual lasers are pumped from a single fibre (not shown) butt-coupled to a single waveguide which is split using 3 dB power splitters into 4 waveguides coupled to the array of 4 waveguide lasers through adiabatic tapers. The Bragg gratings at the far end are made highly reflective and spectrally broad compared to the Bragg gratings at the near end, thus the laser outputs are predominantly from the near end. The laser outputs are multiplexed together by the power splitters into the input waveguide and collected by the pump fibre.

Figure 4 shows a measured output spectrum from a four-channel waveguide laser array made according to the present invention in a configuration corresponding to the one shown in Figure 3. The waveguide laser array structure was designed to 50 GHz channel

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<sup>1</sup> D. L. Veasey et al. "Arrays of distributed-Bragg-reflector waveguide lasers at 1536 nm in Yb/Er codoped phosphate glass", Appl. Phys. Lett., Vol. 74, No. 6, February 1999, pp. 789 – 791

spacing (= 0.41 nm) by selecting four appropriate widths from the design curve exhibited on Figure 2A.

Figure 5 shows measured laser output peak positions as function of temperature

- 5 corresponding to the spectral trace in Figure 4. As the temperature is increased the peaks move towards higher wavelengths with 10.5 pm/°C, however, the spacing between the individual channels show no dependence on temperature within the measurement precision (10 pm) in the temperature interval.
- 10 Figure 6 shows a schematic view of an array of 4 buried planar waveguide lasers coupled to a 1-to-4 splitter/combiner tree as in Figure 3. This embodiment differs from the one depicted in Figure 3 by the employed taper sections inside the waveguide laser cavities. Small taper sections are introduced inside each cavity, tapering the cavity width to a mean width identical to all the waveguide laser array cavities. This approach helps equalising
- 15 the gain inside the cavities, resulting in a more uniform power output in the emitted laser wavelengths. The Bragg wavelengths are not affected by this approach, as the Bragg wavelengths are determined by the waveguide width at the grating positions. The waveguide widths at the grating positions are not affected by the tapers added inside the cavities.

20

Figure 7 shows the derivative of the design curve exhibited in Figure 2A. To successfully fabricate an array of waveguide lasers spanning a large number of standard ITU channels using the method according to the present invention, the obtained design curve must fulfil two distinct requirements. First, it is mandatory that a wide wavelength range be

- 25 encompassed by the curve. Second, it is crucial that the design curve,  $\lambda_B(w)$ , is a monotonically increasing function of the waveguide widths  $w$ , and that the derivative is a softly varying function. A wide wavelength range is needed to encompass a large number of standard ITU channels. The softly varying derivative is required, such that the incremental waveguide width needed to step from a given ITU channel to the next ITU
- 30 channel neither is too small, nor too large. If very small incremental widths are required the spectral position of the laser outputs and hence channel spacing are very easily influenced by process fluctuations in the fabrication process.

**DETAILED DESCRIPTION**

The present invention concerns a multi-wavelength emitting laser device based on silica-on-silicon planar optical waveguides. Moreover, it allows for a large span of the emitted wavelengths by variation of the dimensions of the employed waveguides, and for

- 5 subsequent tuning of the emitted wavelengths by forming Bragg gratings in the waveguides using actinic radiation. Said Bragg gratings can be individually tuned using a focused beam of actinic radiation. It also provides a multi-wavelength emitting laser device with superior thermal and mechanical stability towards external influences.
- 10 With reference to Figure 1, these features are achieved by burying, in a planar silica structure 12 + 14 on a silicon substrate 21, closely spaced parallel nearly rectangular silica waveguides with predetermined variation in widths translating into a predetermined variation in effective refractive indices. The waveguide cores 13 are co-doped at least with germanium and erbium, and preferably also aluminium and ytterbium. Furthermore, Bragg
- 15 gratings 31 and 32 are imprinted into the waveguides by irradiating the waveguides with coherent actinic radiation through a phasemask. Those Bragg gratings constitute a laser resonator structure in each of the waveguides, emitting in different predetermined wavelengths.
- 20 The basic structure of the waveguide is traditional and consists of substrate 21 - undercladding 12 - waveguide cores - topcladding 14 reflowed over the cores. Some general features of the waveguide structure, its properties and the Bragg gratings will now be given, and a more detailed description of the fabrication process will be given later on.
- 25 The waveguide cores are placed on a silica buffer layer 12 of sufficient thickness, to render coupling of optical energy from the waveguides to the substrate 21 negligible. For typical waveguides having a refractive index step of approximately  $10^{-2}$  compared to the silica buffer layer 12, a thickness of 10  $\mu\text{m}$  or more is preferred for the buffer layer. The silica buffer layer 12 is obtained by thermally oxidising the silicon substrate, or
- 30 alternatively, by depositing using a suitable silica deposition method a layer of silica on at least one side of the silicon substrate.

Silicon has thermal conductivity two orders of magnitude larger than silica, and can therefore eliminate local temperature fluctuations from external influences, ensuring

consistent laser channel spacing. Furthermore, mechanical stability is obtained by the high out-of-plane bending stiffness property of the silicon substrate 21.

Preferably, the waveguide cores 13 are co-doped at least with germanium and erbium, 5 and in most cases also with aluminium and ytterbium, in order to create amplifying waveguides when the device is pumped around 980 nm or 1480 nm. For typical waveguide cores having a refractive index step of approximately  $10^{-2}$  compared to thermally oxidised silicon the preferred height of the waveguide cores is approximately 3 $\mu\text{m}$  or more.

10

In order to establish the waveguides, the cores are covered with a top cladding layer 14 of reflowable boron and phosphorous doped silica glass having a refractive index close to that of the silica buffer 12. Alternatively, the waveguide cores are first covered first with a thin layer of undoped silica glass and subsequently with a layer of reflowable boron and 15 phosphorous doped silica glass. Both glasses having a refractive index close to that of the silica buffer. It is preferred that the thickness of the first undoped layer of silica glass is less than approximately 2  $\mu\text{m}$ . As another alternative, a top cladding 14 entirely made from undoped silica is used, having a refractive index close to that of the silica buffer 12. The total thickness of the top cladding as measured from the top of a waveguide core to 20 the surface of the top cladding is at least approximately 10  $\mu\text{m}$ .

The waveguides should be closely spaced, although not so close that significant exchange of optical energy takes place between neighbouring waveguides. For typical waveguides having a refractive index step of approximately  $10^{-2}$  compared to the silica 25 buffer layer, a waveguide separation of more than approximately 50  $\mu\text{m}$  is preferred. For easy coupling of a multitude of waveguide lasers to a multitude of fibres a separation of the waveguides corresponding to the fibre separation in a fibre ribbon is preferred.

As mentioned earlier, Bragg gratings are imprinted into the waveguides by irradiating the 30 waveguides with coherent actinic radiation through a phasemask. This is to establish laser cavities in the amplifying waveguide cores. The reflected wavelengths are determined by the effective refractive index pertaining to a mode in the waveguide, and by the phasemask period, according to the equation:

$\lambda_B$  is the reflected wavelength (and hence the laser wavelength),  $n_{\text{eff}}(w)$  the effective refractive index of a waveguide of width  $w$ , and  $\Lambda$  is the phasemask period.

- 5 The width  $w$  of a waveguide is defined as the width of the etched core profile before deposition and annealing of the topcladding, hence the width as determined by the phasemask in the UV writing procedure. More precisely,  $w$  is the width of the waveguide core measured in a direction substantially parallel to the substrate and normal to the waveguide centre axis, in a height corresponding to half the height of the core layer. In
- 10 most cases in this text, the width will refer to the width at the position of the DBR gratings, 31 and 32 in Figure 1.

The effective refractive index,  $n_{\text{eff}}$ , is the refractive index experienced by light propagating in some transverse mode through the waveguide. The electromagnetic (EM) field strength 15 of a transverse mode will typically reach into the surrounding cladding. Thereby, the effective refractive index experienced will be a combination of the refractive index  $n_{\text{core}}$  of the core and  $n_{\text{cladding}}$  of the cladding region. If the core is narrow, a large part of the EM field strength of a transverse mode will reach into the cladding region and hence  $n_{\text{eff}}$  will be highly influenced by  $n_{\text{cladding}}$ . Adjusting the width  $w$  of the core thereby means adjusting 20 the contributions from  $n_{\text{core}}$  and  $n_{\text{cladding}}$ , and thereby  $n_{\text{eff}}(w)$ .

Two lasers being equal except from a difference  $\Delta w$  in the waveguide width  $w$  (and hence a difference  $\Delta n_{\text{eff}}$  in the effective refractive index  $n_{\text{eff}}(w)$ ) at the position of the grating, will have a difference  $\Delta \lambda_B$  in their laser wavelength  $\lambda_B$ . This property, a change  $\Delta w$  leads to a 25 change  $\Delta n_{\text{eff}}$  and thereby  $\Delta \lambda_B$ , is an inherent property of the waveguide materials and geometry. The dependency of  $\lambda_B$  and  $n_{\text{eff}}$  on the width of the waveguide is illustrated in Figure 2A and B respectively (unless otherwise stated, reference to Figure 2A and B will be to the curves 42 and 44, where circle + arrow indicates that values should be read off the left axis) which shows  $\lambda_B(w)$  and  $n_{\text{eff}}(w)$  as function of waveguide width,  $\lambda_B(w)$ , curve 30 for one polarisation, obtained for waveguides fabricated according to the present invention. Since the waveguides used in curves 42 and 44 in Figure 2A and B all have the same grating pitch  $\Lambda$ , the dependency  $n_{\text{eff}}(w)$  is analogous to  $\lambda_B(w)$  (formula 1) and, for use in defining the waveguide properties, a more fundamental entity. The background of Figure 2A and B will be described in greater detail later on.

In order to characterise the ability to tune wavelength by adjusting the width of a waveguide, we define  $dn_{\text{eff}}/dw$ , the derivative of  $n_{\text{eff}}(w)$ , as the important parameter expressing the change in laser wavelength for a given change in the width, of the waveguide laser, at the position of the Bragg gratings. It is preferable that  $dn_{\text{eff}}/dw$  is of

- 5 considerable size in order to be able to span a broad wavelength band by varying only the width. On the other hand, a too large value of  $dn_{\text{eff}}/dw$ , which is proportional to the slope of the curve in Figure 2B, may be disadvantageous because of a hypersensitivity of the reflected wavelength upon the width.
- 10 As seen from Figure 2B, the slope of the curve becomes small as the width increases to above  $12\mu\text{m}$ . This is because, as the width of the waveguide core and of the relevant transverse mode becomes comparable in size, the contribution from  $n_{\text{cladding}}$  becomes insignificant, and  $n_{\text{eff}} \approx n_{\text{core}}$  for all practical purposes. A similar effect will arise in the other end of the curve, when the width of the core becomes small, and the contribution from
- 15  $n_{\text{core}}$  becomes insignificant.

The present invention concerns planar waveguide lasers, where at least one of the reflecting means constituting the laser resonator is a Bragg grating, which are characterised by their value of  $dn_{\text{eff}}/dw$ , such as to optimise wavelength tuning by varying

- 20 the width  $w$ . Figure 7 shows a plot 71 of  $d\lambda_B/dw = \Lambda \times dn_{\text{eff}}/dw$  as a function of  $w$ . It is seen that  $d\lambda_B/dw$  is larger than  $0.2 \text{ nm}/\mu\text{m}$  for the given widths. Since in the given case the grating pitch was  $\Lambda = 1071 \text{ nm}$ , the corresponding minimum value of  $dn_{\text{eff}}/dw$  is  $1.9 \times 10^{-4} \mu\text{m}^{-1}$ . The highest value of  $d\lambda_B/dw$  found in the prior art, Veasey *et al.*, is  $\sim 0.1 \text{ nm}/\mu\text{m}$  corresponding to  $dn_{\text{eff}}/dw = 1.0 \times 10^{-4} \mu\text{m}^{-1}$  ( $\Lambda = 1015.6 \text{ nm}$ ). The reason for these
- 25 differences belongs to the difference in refractive index profile of the waveguide core, which will be described in further detail later.

Preferably  $dn_{\text{eff}}/dw$  is in the interval between  $1.0 \times 10^{-4} \mu\text{m}^{-1}$  and  $20.0 \times 10^{-4} \mu\text{m}^{-1}$  in order to ensure a reasonable wavelength span for varying widths and on the other hand a

- 30 reasonable sensitivity of the tuning.

By exploiting and optimising the above relations, it is obtained that variation of waveguide widths  $w$  of the well-defined nearly rectangular waveguides give rise to a large variation in the effective refractive index  $n_{\text{eff}}(w)$ , and hence laser wavelength  $\lambda_B$ , making it possible to

- 35 span several standard ITU channels. In other word, waveguide lasers with Bragg gratings

having the same spatial periodicity can be tuned by varying their width, which is a very convenient and easy way of tuning the laser wavelength.

It is possible to employ a phasemask that contains several (N) parallel gratings of varying,

- 5 definite period,  $\Lambda_1, \Lambda_2, \dots, \Lambda_N$ , co-ordinated with several groups of closely spaced waveguides on the wafer, each group consisting of waveguides having varying widths. Due to the close spacing, it is possible to align the phasemask to the underlying waveguides to form a multitude of groups containing a multitude of lasers all with distinct predetermined wavelengths. Such an arrangement can span an even wider range of
- 10 standard ITU channels, since tuning properties of the grating pitch and the waveguide width are combined.

The laser frequency of individual lasers may be separated by any interval larger than the linewidth of a single mode, so as to agree with the spacing of ITU channels. Typical ITU

- 15 standards are 100 GHz and 50 GHz for each channel, corresponding to wavelength intervals of 0.82 nm and 0.41 nm respectively. However, it is feasible with the multi-wavelength emitting laser device of the present invention to have centre frequencies of single modes separated by 25 GHz, 12.5 GHz or 10.0 GHz or any frequency interval in between the mentioned intervals. Since an ITU channel allows for small (12.5%)
- 20 variations these frequency separations translates into intervals 75 - 125 GHz, 37.5 - 62.5 GHz, 18.75 - 31.25 GHz, 9.375 - 15.615 GHz and 7.5 - 12.5 GHz

By placing the waveguides in close proximity, macroscopic variations in the silica layers across the substrate can be neglected. Thereby, the variation of the waveguide widths

- 25 translates directly into a variation of the effective refractive index of the waveguides. Also, it is obtained in that macroscopic variations in the photolithography and etching steps, utilised in the definition of the waveguide cores, can be neglected. Further, it is obtained in that a large number of waveguides can fit under a standard phasemask at one time, and that Bragg gratings can be imprinted with a single exposure session using coherent
- 30 actinic radiation. Thus, Bragg gratings can be made simultaneously, with a high degree of precision, in several well-defined waveguides, making it possible to precisely control the position of the emitted wavelengths.

Using UV-writing, it is furthermore obtained that the precise position of the emitted wavelengths can be fine-tuned in a post processing step, using a focused beam of actinic radiation, scanning the previously fabricated Bragg gratings.

- 5 The multi-wavelength emitting laser resonator structures can be realised in several ways, with the laser resonator structures are made either as distributed Bragg-reflector or distributed feedback types. Some of these will be discussed, with reference to Figure 1, 3 and 6. In most cases, the Bragg gratings 31 and 32 are formed by exposure with coherent actinic radiation through a suitable phasemask. In some cases one of the gratings can be
- 10 replaced by a highly reflective dielectric mirror. Typically, the waveguide structure is high pressure loaded with deuterium or hydrogen previous to the exposure.

In a first embodiment, the laser resonator structures is of the distributed Bragg-reflector type, where one Bragg grating 32 is substituted by another highly reflective means, such

- 15 as a dielectric mirror (not shown), positioned at the facets on one end of the waveguides. The other Bragg grating 31 is then formed by exposure of the waveguides with coherent actinic radiation through a suitable phasemask.

In a second embodiment, the multi-wavelength emitting laser resonator structure is of the

- 20 distributed Bragg-reflector type, where the Bragg-reflector 32 in one end has very high reflectance and is very broad band. The Bragg-reflector 31 at the other end then exhibit lower reflectance and only reflects in a very narrow wavelength range around each of the predetermined wavelengths.

- 25 Having formed the multi-wavelength emitting waveguide laser resonator structure, it is often desirable to multiplex the laser outputs together. This is shown in Figure 3, where the multiplexing is carried out by power splitters 16 and 17 into the input waveguide 15. The waveguide are coupled to the multiplexers through adiabatic tapers 18.
- 30 In a third preferred embodiment, the multi-wavelength emitting waveguide laser resonator structure is formed using two sampled Bragg gratings, having constant but slightly different spacing between reflection peaks in their respective spectra. A sampled grating consists of a number of short grating sections with equal length L1 separated an equal distance L2 from each other. Sampled gratings offer multi-peak reflection with good
- 35 control over the spectral distance between the peaks. By slightly varying the effective

refractive index at the position of one of the sampled gratings, the reflection peak spectrum will move slightly. As the reflection peak spectrum moves, different peaks in the two reflection spectra will overlap at different times, selecting different laser wavelengths. In this way a large number of ITU channels can be obtained by slight variation of the

5 effective refractive index through the waveguide width at the position of one of the sampled gratings.

In a fourth embodiment, shown in Figure 6, the multi-wavelength emitting waveguide laser resonator structure is formed using any of the above reflector configurations. In order for

10 the laser cavities to be of the same size, tapered parts 19 are defined close to the gratings 31 and 32. This permits equal volumes of amplifying waveguide core 13 in the cavities at the same time as a variation in the waveguide width w at the position of the gratings for tuning purposes. This tapering can be favourable because the output power to some degree depends on the size of the active regions, and it is desired to have equal output

15 powers from the lasers.

The optical waveguide structure 11 holding an array of planar waveguide lasers is prepared by a combination of different standard clean room thin film techniques, such as thermal oxidation of silicon, Plasma Enhanced Chemical Vapour Deposition (PECVD) of

20 doped and un-doped silica, photolithography and Reactive Ion Etching (RIE) of silica.

First, a standard silicon wafer 21 is RCA-cleaned and thermally oxidised to give an oxide layer 12 with a thickness of at least 10 µm. The resulting oxide is to be used as buffer cladding for the waveguide cores. Second, using PECVD an approximately 5 µm thick

25 layer of aluminium- and erbium-doped germanosilicate core glass is deposited on the top of the silica buffer layer, and subsequently annealed. The PECVD process uses silane, germane and nitrous oxide as precursors for the deposition of the germanosilicate. Aluminium and erbium are supplied from a liquid source containing Al- and Er-chelate dissolved in an organic solution. The liquid flow is metered, flash-evaporated and

30 subsequently driven into the PECVD reactor with a carrier gas.

Waveguide cores 13 are defined in the core glass layer using standard photolithography and RIE. Finally, the etched cores are covered with an approximately 12 µm thick cladding layer 14 of boron- and phosphorous doped silica, which is subsequently

35 annealed. By employing a top cladding structure composed of a first thin layer of undoped

silica glass followed by a layer of boron- and phosphorous-doped glass, inter-diffusion of dopants between the doped top cladding layer and the core is minimised, hence maintaining the advantageous nearly rectangular refractive index profile. The melting point for the doped core material is so high that the final annealing of the topcladding does

5 not alter the nearly rectangular index profile of the core significantly.

Note, that the glass layers 12 and 14, and waveguide cores 13 described above may be formed by other means, and may contain further dopants. For example, the silica layers can be deposited using flame hydrolysis deposition, and may be doped using e.g. solution

10 doping. Also the dopant ytterbium may conveniently be added to the core glass structure.

The Bragg gratings 31 and 32, used to define the laser cavities are imprinted into the waveguide cores using 248 nm excimer UV-laser light through a zero-order nulled phasemask with a fixed periodicity of 1071 nm. Any type of actinic light can in principle be

15 applied for writing. The used 3 mm wide and 50 mm long phasemask covers the waveguide array during exposure. By scanning the UV beam, exposure is performed in both ends of the waveguide cores 13 constituting the waveguide array 11, leaving a region unexposed in the centre.

20 Prior to the exposure session, the wafer with the completed waveguide structure 11 is high-pressure deuterium loaded to significantly enhance photosensitivity of the core glass. After the Bragg gratings 31 and 32 have been fabricated in the exposure session, the waveguide laser array is post annealed at approximately 200 degrees centigrade for typically half an hour to stabilise the gratings by removing short-lived unstable

25 components of the UV-induced refractive index change.

A single waveguide laser fabricated according to the above described method, have given output of 0.4 mW at 1553 nm for a pumping power of 265 mW at 979 nm.

30 In order to obtain a precisely defined constant channel spacing between the laser outputs it is necessary to know the Bragg wavelength as function of the waveguide width,  $\lambda_B(w)$ . This function, of which an example is displayed in Figure 2A, has a number of constant parameters such as the waveguide height and the refractive index step, as well as more subtle parameters from the fabrication process, such as the exact waveguide core shape

35 and e.g. annealing influences.

Although, in principle, it is possible to calculate  $\lambda_B(w)$  by calculating  $n_{eff}(w)$ , it is preferred that  $\lambda_B(w)$  is determined experimentally. This is done by imprinting weak Bragg gratings into an array of waveguide cores of increasing width  $w$ , and then for each waveguide

5 measure the Bragg wavelength. The resulting  $\lambda_B(w)$  42 as shown in Figure 2A is then used as a design function pertaining to the applied waveguide fabrication process and the used phasemask. However, it is straightforward to obtain a new  $\lambda_B(w)$  using the same waveguide fabrication process by using a phasemask with a different period  $\Lambda$ .

10 From  $\lambda_B(w)$  the waveguide widths resulting in a constant channel spacing are inferred. A new photomask can then be designed holding a pattern defining waveguides of correct width resulting in the desired laser structures. Therefore, a curve  $\lambda_B(w)$  is called a design curve.

15 The invention is further illustrated by the following examples of preparation of a design curve  $\lambda_B(w)$ , and another example where said design curve  $\lambda_B(w)$  is used to fabricate a four-channel laser device having a multiplexed nearly equidistantly channel spacing of 50 GHz. Also an example of temperature tuning and temperature stability of the laser output will be shown.

20

#### Example 1

A design curve 42 as given in Figure 2A showing the Bragg wavelength  $\lambda_B(w)$  as function of waveguide width, or alternatively Figure 2B showing  $n_{eff}(w)$ , is needed for the fabrication of waveguide laser structures emitting at predetermined wavelengths.

25

For this purpose a buried waveguide structure was made holding an array of 30 waveguide lasers designed conceptually as depicted in Figure 1. The individual cavities (formed in the waveguide cores 13) of the array were spaced 125  $\mu m$  centre-to-centre, and had nominal widths from 4  $\mu m$  to 12.7  $\mu m$  in constant step of 0.3  $\mu m$ . A single set of

30 Bragg gratings 31 were imprinted into the waveguide cores 13, thus the Bragg gratings 32 were omitted. The Bragg gratings 31 were made using UV-exposure (248 nm) through a zero-order nulled phasemask with a fixed periodicity of 1071 nm. Spectrally broad light from an erbium-doped fibre based amplified spontaneous emission (ASE) light source was successively coupled to each of the waveguide cores 13 using a butt-coupled fibre.

35

Light transmitted through the waveguide core 13 and the grating 31 was collected at the opposite end using another butt-coupled fibre, and subsequently fed to a spectrum analyser where the position of the transmission dip was recorded, ultimately yielding the curve 42 on Figure 2A. The curve 42 shows the versatility of the fabrication method

5 according to the present invention. By varying the widths of the waveguide cores 13 from 4 µm to 12.7 µm a Bragg wavelength span of more than 5 nm is obtained, making it possible to span several standard ITU channels.

#### Example 2

10 For the purpose of demonstrating the applicability of the method according to the present invention, a four-channel planar waveguide laser array with integrated power splitters/combiners was designed, using the design curve from example 1, and fabricated. In a silicon substrate 21 an approximately 12 µm thick buffer layer 12 of thermal oxide was grown, as shown in Figure 3. An approximately 5 µm thick layer of erbium and

15 aluminium doped germanosilicate core glass was deposited using PECVD and subsequently annealed. Waveguide widths that should render it possible to fabricate an array of lasers with 50 GHz channel spacing were inferred from the curve 42 on Figure 2A. The 4 waveguides 13 in the laser array design were coupled through adiabatic tapers 18 to a 1-to-4 y-splitter/combiner tree 16 and 17, ending in one waveguide 15. The

20 waveguide laser array and splitter/combiner structure was transferred into the erbium and aluminium germanosilicate using a combination of standard clean room photolithography and RIE. Finally, the etched structure was covered by a layer 14 of top cladding glass, and annealed.

25 Prior to Bragg grating fabrication, the entire structure was deuterium loaded to significantly increase the photosensitivity of the core glass. Bragg gratings with lengths and strengths of approximately 10 mm (reflection > 99.9 %, 1 nm wide) 31, and 10 mm (reflection approximately 95 %, 3 dB width of < 0.3 nm) 32 were imprinted into the waveguides 13, as described in example 1, leaving a 10 mm region in between

30 unexposed. The comparatively high reflectance of the Bragg gratings 32 was made so that laser power was primarily emitted from the individual laser through the gratings 31, and into the 1-to-4 splitter/combiner structure and finally to the waveguide 15 back into the launching fibre. The collected resulting laser output was then separated from the pump using a fibre WDM and analysed by an optical spectrum analyser.

The spectral output, when the laser array is pumped at 980 nm, is shown in Figure 4, where the peaks 51, 52, 53, and 54 each represents an output from 1 of 4 of the lasers in the planar waveguide laser array. The widths of the waveguides 13 were designed to give an equidistant channel spacing of 50 GHz. Examining the position of the 4 peaks 51 – 54 5 yields that the channel spacing is almost constant, with a channel spacing of 51.1 GHz between peaks 51 and 52, 45.3 GHz between peaks 52 and 53, and finally 41.4 GHz between peaks 53 and 54.

### Example 3

For the purpose of demonstrating the excellent temperature stability and temperature

10 tuning possibilities of a planar waveguide laser array fabricated according to the present invention, the 4-channel laser array described in example 2 was put to test.

The waveguide laser array was placed on a temperature controllable mount, and a pump/collecting fibre was butt-coupled to the single waveguide 15, and through a fibre WDM leading the collected laser outputs to an optical spectrum analyser. The

15 temperature of the mount was linearly ramped from 13.5 to 76 degrees centigrade, and temperature as well as corresponding peak positions for each of the 4 laser outputs was recorded. The results of this measurement are shown in Figure 5, where the laser wavelength position of each of the 4 laser outputs from the array is plotted as function of mount temperature.

20

The curves on Figure 5 show excellent channel spacing stability as the temperature is raised. The spacing between the individual channels show no dependence on temperature within the measurement precision (10 pm) in the temperature interval from 13.5 to 76 degrees centigrade. As the temperature of the mount is raised, the output

25 peaks from the laser array move linearly towards higher laser wavelengths with a rate of 10.5 pm/degree centigrade. As the channel spacing between each of the laser outputs remain constant, this collective translation of the outputs can be used to precisely position the outputs from the laser array on a number of consecutive ITU channels.

30 In the table below are listed ITU wavelengths for the ITU channels (frequencies) 193.00 THz to 193.20 THz, as well as laser wavelengths at two different temperatures for the device discussed in the present example.

| ITU |                 | Laser output wavelengths (nm) |           |
|-----|-----------------|-------------------------------|-----------|
| THz | Wavelength (nm) | @ 16 °C                       | @ 57.7 °C |
|     |                 |                               |           |

|        |          |          |          |
|--------|----------|----------|----------|
| 193.00 | 1553.329 |          | 1553.292 |
| 193.05 | 1552.926 | 1552.866 | 1552.948 |
| 193.10 | 1552.524 | 1552.520 | 1552.578 |
| 193.15 | 1552.122 | 1552.152 | 1552.158 |
| 193.20 | 1551.721 | 1551.736 |          |

The presented numbers in the table clearly show that it is possible to position the outputs from the planar waveguide laser array on the ITU grid and, furthermore, to select between different sets of channels, depending upon the temperature.

## CLAIMS

1. A laser system comprising a first and a second laser,

5 the first laser comprising:

- a first substrate holding a first waveguide structure, said first waveguide structure having a core and a cladding region, wherein the core region comprises an active region holding one or more dopants,

10

- a first and a second reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the laser cavity supports a first laser mode, said first laser mode experiencing a first effective refractive index,  $n_{eff1}$ , at the position of the first reflective member, and wherein the core region has a width,  $w_1$ , at  
15 the position of the first reflective member,

the second laser comprising:

20 - a second substrate holding a second waveguide structure, said second waveguide structure having a core and a cladding region, wherein the core region comprises an active region holding one or more dopants,

25 - a third and a fourth reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the laser cavity supports a second laser mode, said second laser mode experiencing a second effective refractive index,  $n_{eff2}$ , at the position of the third reflective member, and wherein the core region has a width,  $w_2$ , at the position of the third reflective member,

characterised in that

30

$n_{eff1}$  is different from  $n_{eff2}$  and that the first and second waveguide structures are adapted to provide, at the positions of the first and third reflective members, a dependency of the effective refractive indices upon the core widths,  $n_{eff1}(w_1)$  and  $n_{eff2}(w_2)$ , satisfying  $dn_{eff1}/dw_1 > 2 \times 10^4 \mu\text{m}^{-1}$  and  $dn_{eff2}/dw_2 > 2 \times 10^4 \mu\text{m}^{-1}$ .

35

2. A laser system according to claim 1, wherein  $dn_{eff1}/dw_1$  and  $dn_{eff2}/dw_2$  is within the range  $2 \times 10^{-4} - 20 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $3 \times 10^{-4} - 15 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $4 \times 10^{-4} - 10 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $5 \times 10^{-4} - 8 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $6 \times 10^{-4} - 7 \times 10^{-4} \mu\text{m}^{-1}$ .

5

3. A laser system comprising a first and a second laser,

the first laser comprising:

10 - a first substrate holding a first waveguide structure, said first waveguide structure having a core and a cladding region, wherein the core region comprises an active region holding one or more dopants,

15 - a first and a second reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the first waveguide structure has a first core width,  $w_1$ , at the position of the first reflective member, and, wherein the laser cavity supports a first laser mode, said first laser mode experiencing a first effective refractive index,  $n_{eff1}$ , at the position of the first reflective member, wherein  $n_{eff1}$  is associated with a first refractive index profile, and

20

the second laser comprising:

25 - a second substrate holding a second waveguide structure, said second waveguide structure having a core and a cladding , wherein the core region comprises an active region holding one or more dopants, and

30 - a third and a fourth reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the second waveguide structure has a second core width,  $w_2$ , at the position of the third reflective member, and, wherein the laser cavity supports a second laser mode, said second laser mode experiencing a second effective refractive index,  $n_{eff2}$ , at the position of the third reflective member, wherein  $n_{eff2}$  is associated with a second refractive index profile,

characterised in that

35

$n_{\text{eff}1}$  is different from  $n_{\text{eff}2}$ ,

$w_1$  is different from  $w_2$ , and that

$$\frac{n_{\text{eff}2} - n_{\text{eff}1}}{w_2 - w_1} \text{ is larger than } 2 \times 10^{-4} \mu\text{m}^{-1}.$$

4. A laser system according to claim 3, wherein  $\frac{n_{\text{eff}2} - n_{\text{eff}1}}{w_2 - w_1}$  is within the range  $2 \times 10^{-4} - 20 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $3 \times 10^{-4} - 15 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $4 \times 10^{-4} - 10 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $5 \times 10^{-4} - 8 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $6 \times 10^{-4} - 7 \times 10^{-4} \mu\text{m}^{-1}$ .
5. A laser system according to any one of the preceding claims, wherein the first and second laser cavities are single-mode laser cavities emitting laser light at a first and a second centre frequency, respectively.
6. A laser system according to claim 5, wherein the difference between the first and second centre frequencies is within the range 125 - 1000 GHz, or within the range 75 - 125 GHz, or within the range 37.5 - 62.5 GHz, or within the range 18.75 - 31.25 GHz, or within the range 9.375 - 15.615 GHz, or within the range 7.5 - 12.5 GHz, or within the range 1 - 7.5 GHz.
7. A laser system according to any one of the preceding claims, wherein the first and second substrates form part of the same silicon substrate.
8. A laser system according to claim 7, wherein at least part of the cladding region is fabricated by thermally oxidising the silicon substrate.
9. A laser system according to any one of the preceding claims, wherein the one or more dopants comprise one or more substances selected from the group consisting of germanium, erbium, aluminium, ytterbium and neodymium.
10. A laser system according to any one of the preceding claims, wherein the first and third reflective members are formed by refractive index modulations in the core regions.
11. A laser system according to claim 10, wherein the first and third reflective members each defines a substantially periodic grating structure in the core regions.

12. A laser system according to any one of the preceding claims, wherein the first and second waveguide structures define a first and second centre axis, respectively, and wherein the shortest distance between the first and second centre axis is larger than 10 5  $\mu\text{m}$ , such as larger than 50  $\mu\text{m}$ , such as larger than 60  $\mu\text{m}$ , such as larger than 70  $\mu\text{m}$ , such as larger than 80  $\mu\text{m}$ , such as larger than 100  $\mu\text{m}$ , such as larger than 125  $\mu\text{m}$ , such as larger than 150  $\mu\text{m}$ , such as larger than 250  $\mu\text{m}$ .

13. A laser system according to any one of the preceding claims, wherein the centre 10 wavelengths of the light emitted from the first and second laser cavities are within the region from 500nm to 2000 nm, such as within the region 750nm to 900nm or 1300nm to 1650nm, preferably within the range 1528 - 1620 nm or 1300 - 1400 nm or 100 - 1150 nm.

14. A laser system according to any one of the preceding claims, wherein the power 15 emitted from the first and second laser cavities is within the range 0.005 - 100 mW.

15. A laser system according to any one of the preceding claims, further comprising a light source for pumping the active region of the first and/or second laser, wherein said light source has a wavelength within the range of 930 - 990 nm, 1470 - 1490 nm or 750 - 850 20 nm.

16. A single-mode laser emitting light around a centre wavelength,  $\lambda$ , said laser comprising

25 - a substrate holding a waveguide structure, said waveguide structure having a core and a cladding region, wherein the core region comprises an active region holding one of more dopants,

30 - a first and a second reflective member each being formed in the core region so as to form a laser cavity with the active region, wherein the core region has a width, w, at the position of the first reflective member,

characterised in that

the waveguide structure is adapted to provide a dependency of the centre wavelength upon the core width, w, at the position of the first reflective member,  $\lambda(w)$ , satisfying  $d\lambda/dw \geq 0.2 \text{ nm}/\mu\text{m}$ .

- 5 17. A single-mode laser according to claim 16, wherein  $d\lambda/dw$  is within the range 0.2 - 2 nm/ $\mu\text{m}$ , such as within the range 0.3 - 1.5 nm/ $\mu\text{m}$ , such as within the range 0.4 - 1 nm/ $\mu\text{m}$ , such as within the range 0.5 - 0.8 nm/ $\mu\text{m}$ , such as within the range 0.6 - 0.7 nm/ $\mu\text{m}$ .
- 10 18. A single-mode laser according to claim 16 or 17, wherein the substrate is made of silicon, and, wherein at least part of the cladding region is fabricated by thermally oxidising the silicon substrate.
- 15 19. A single-mode laser according to any of claims 16 to 18, wherein the one or more dopants comprise one or more substances selected from the group consisting of germanium, erbium, aluminium, ytterbium and neodymium.
- 20 20. A single-mode laser according to any of the claims 16 to 19, wherein the first reflective member is formed by refractive index modulations in the core region.
- 20 21. A single-mode laser according to claim 20, wherein the first reflective member define a substantially periodic grating structure in the core region.
22. A single-mode laser according to any of claims 16 to 21, wherein the centre wavelength of the emitted light is within the region from 500 nm to 2000 nm, such as 25 within the region 750 nm to 900 nm or 1300 nm to 1650 nm, preferably within the range 1528 - 1620 nm, or 1300 - 1400 nm or 1000 - 1150 nm.
23. A single-mode laser according to any of claims 16 to 22, wherein the power emitted from the laser cavity is within the range 0.005 - 100 mW.
- 30 24. A single-mode laser according to any of claims 16 to 23, further comprising a light source for pumping the active region of the laser, wherein said light source has a wavelength within the range of 930 - 990 nm, 1470 - 1490 nm or 750 - 850 nm.

25. A laser system comprising two or more single-mode lasers according to any of the claims 16 to 24, wherein the single-mode lasers have different widths at the positions of their first reflective members whereby each single-mode laser emit light with different centre frequencies, said centre frequencies being separated by predetermined distances.

5

26. A laser system according to claim 25, wherein the predetermined distances between two neighbouring centre frequencies is within the range 125 - 1000 GHz, or within the range 75 - 125 GHz, or within the range 37.5 - 62.5 GHz, or within the range 18.75 - 31.25 GHz, or within the range 9.375 - 15.615 GHz, or within the range 7.5 - 12.5 GHz, or  
10 within the range 1 - 7.5 GHz.

27. A method of fabricating a laser emitting light at a predetermined wavelength, said method comprising the steps of:

15 forming a first waveguide structure having a core and a cladding region,

providing an active region within the core region, and

forming a first and a second reflective member in the core region so as to form a laser  
20 cavity with the active region, said laser cavity being adapted to support a laser mode, the core having a width w at the position of the first reflective member,

characterised in that

25 at the position of the first reflective member, a refractive index profile of the waveguide structure is formed by adjusting the core width, w, so as to provide a predetermined spatial overlap with a profile of the laser mode so as to obtain the predetermined wavelength of the laser mode.

30 28. A method according to claim 27, wherein the predetermined overlap at least partly determines an effective refractive index,  $n_{\text{eff}}$ , experienced by the laser mode at the position of the first reflective member, and wherein the refractive index profile is adapted to provide, at the position of the first reflective member, a dependency of the effective refractive index upon the core width,  $n_{\text{eff}}(w)$ , satisfying  $dn_{\text{eff}}/dw > 2 \times 10^{-4} \mu\text{m}^{-1}$ .

29. A method according to claim 27 or 28, wherein  $d\text{n}_{\text{eff}}/dw$  is within the range  $2 \times 10^{-4}$  -  $20 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $3 \times 10^{-4}$  -  $15 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $4 \times 10^{-4}$  -  $10 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $5 \times 10^{-4}$  -  $8 \times 10^{-4} \mu\text{m}^{-1}$ , such as within the range  $6 \times 10^{-4}$  -  $7 \times 10^{-4} \mu\text{m}^{-1}$ .

5

30. A method according to any of claims 27 to 29, wherein the step of forming the first and second reflective members comprises the step of forming the first reflective member by forming a Bragg grating in the core region.

10 31. A method of adjusting relative wavelengths of a first and a second laser, said method comprising the steps of:

providing the first laser comprising:

15 - a first substrate holding a first waveguide structure, said first waveguide structure having a core and a cladding region defining a refractive index profile for the first waveguide structure, the core region comprising an active region holding one or more dopants,

20 - a first and a second reflective member each being formed in the core region so as to form a first laser cavity with the active region, said first laser cavity being adapted to support a first laser mode,

wherein, at the position of the first reflective member, a refractive index profile is formed  
25 by adjusting a core width,  $w_1$ , so as to provide a first predetermined spatial overlap with a profile of the first laser mode so as to obtain a predetermined first wavelength,  $\lambda_1$ , of the laser mode,

providing the second laser comprising:

30

- a second substrate holding a second waveguide structure, said second waveguide structure having a core and a cladding region defining a refractive index profile for the second waveguide structure, the core region comprising an active region holding one or more dopants,

35

- a third and a fourth reflective member each being formed in the core region so as to form a second laser cavity with the active region, said second laser cavity being adapted to support a second laser mode,

5 where in, at the position of the third reflective member, a refractive index profile is formed by adjusting a core width,  $w_2$ , so as to provide a second predetermined spatial overlap with a profile of the second laser mode so as to obtain a predetermined second wavelength,  $\lambda_2$ , of the laser mode, and

10 adjusting the core widths  $w_1$  and  $w_2$  so as to provide a predetermined relation between the first and the second wavelength.

32. A method according to claim 31, wherein the core widths  $w_1$  and  $w_2$  and the predetermined relation between the first and the second wavelength fulfil  $\frac{\lambda_2 - \lambda_1}{w_2 - w_1} \geq 0.2$

15 nm/μm.

33. A method according to claim 32, wherein  $\frac{\lambda_2 - \lambda_1}{w_2 - w_1}$  is within the range 0.2 - 2 nm/μm, such as within the range 0.3 - 1.5 nm/μm, such as within the range 0.4 - 1 nm/μm, such as within the range 0.5 - 0.8 nm/μm, such as within the range 0.6 - 0.7 nm/μm.

20 34. A method according to any of claims 31 to 33, wherein the first and third reflective members are formed by Bragg gratings having at least substantially the same period.

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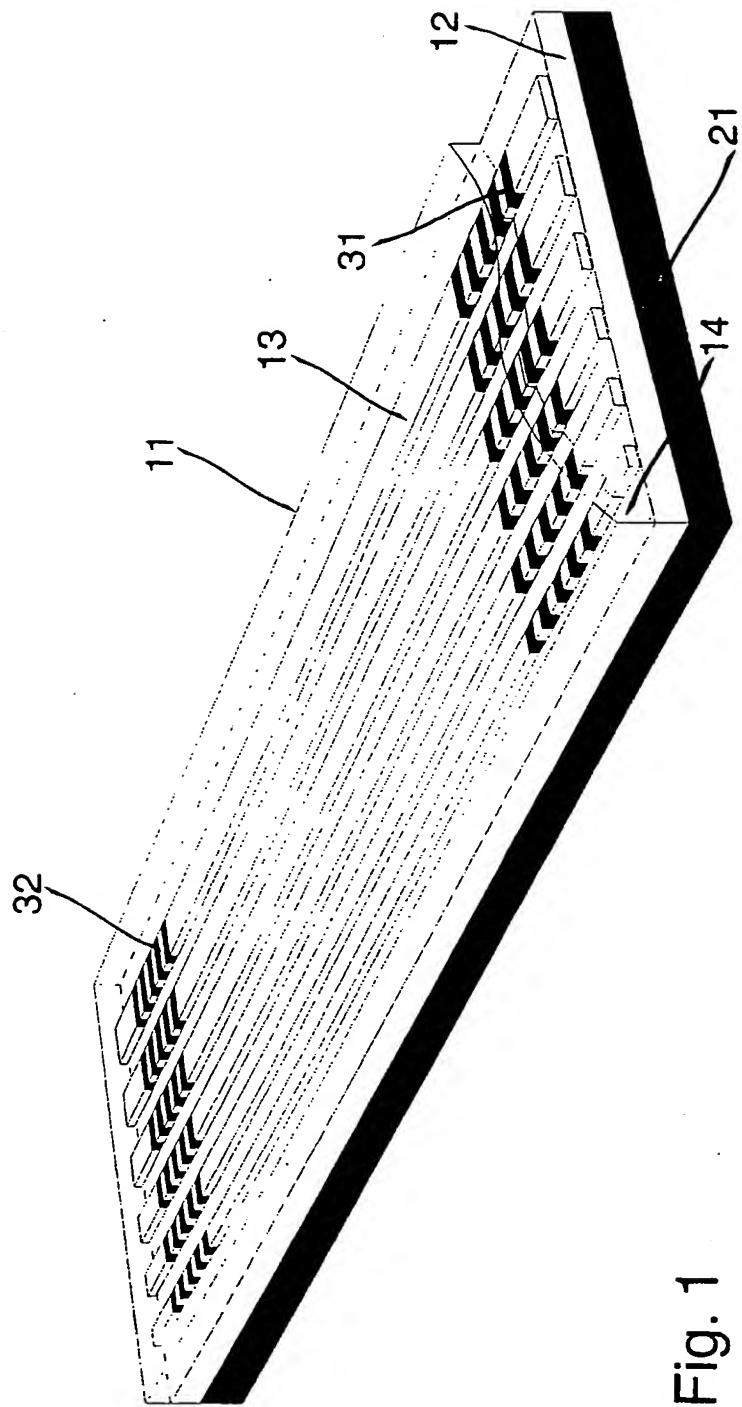
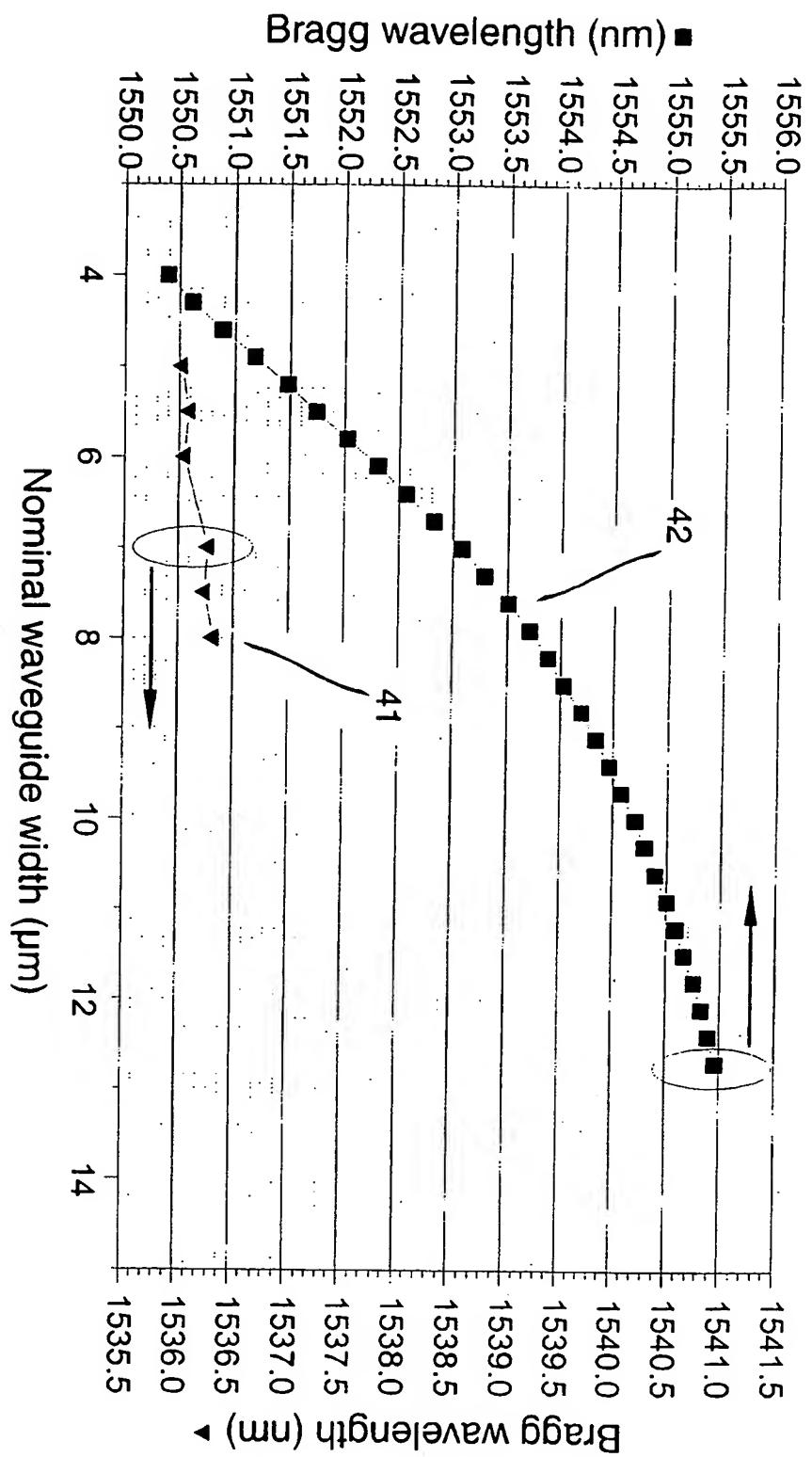
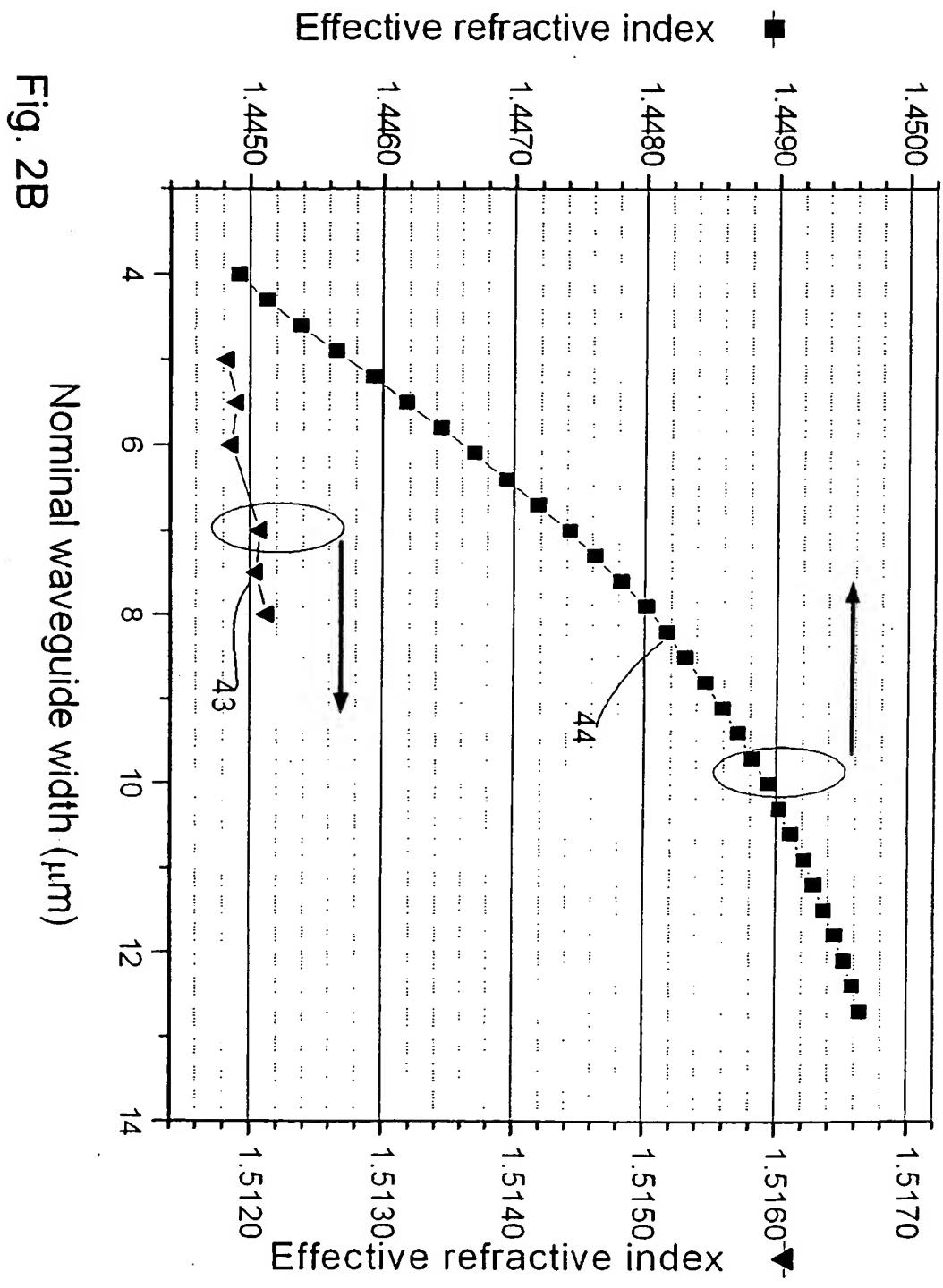


Fig. 1



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Fig. 2A



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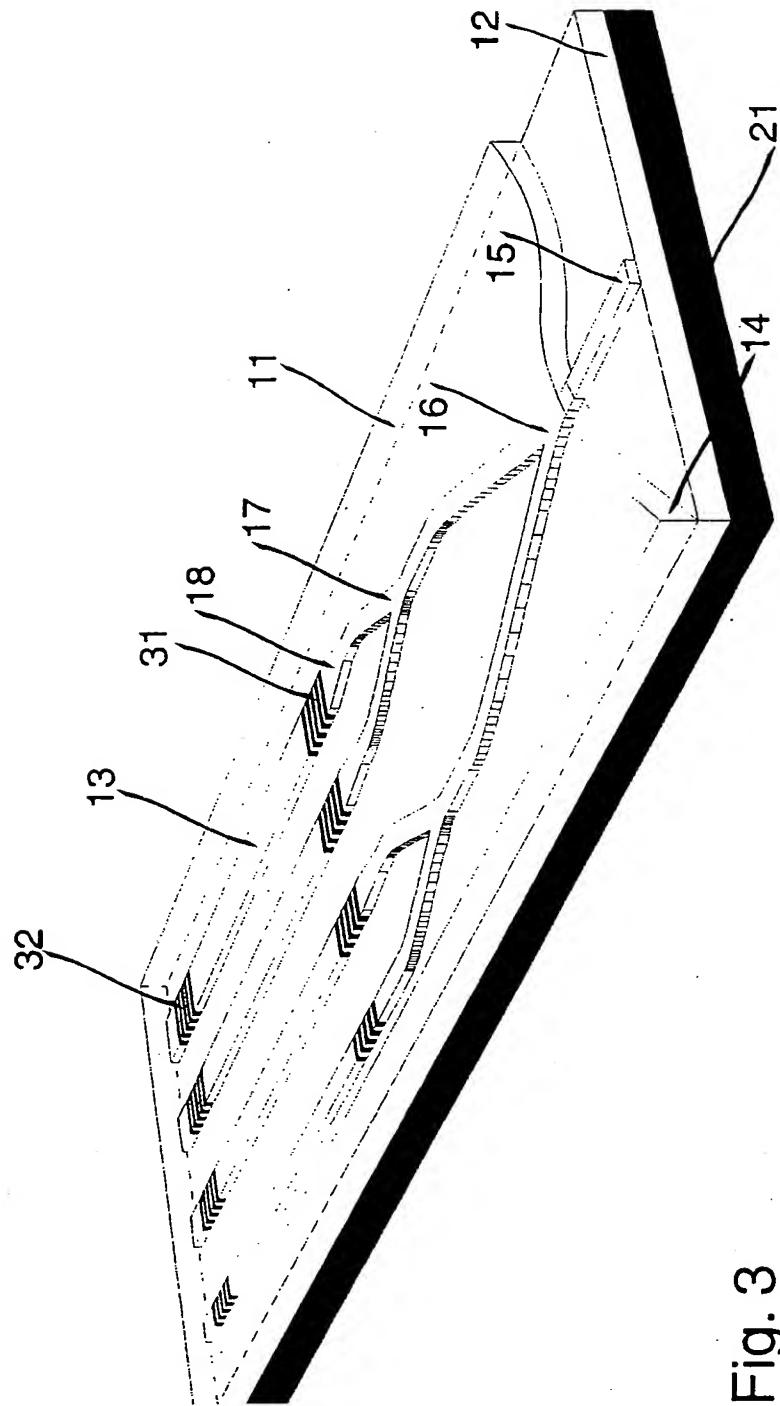


Fig. 3

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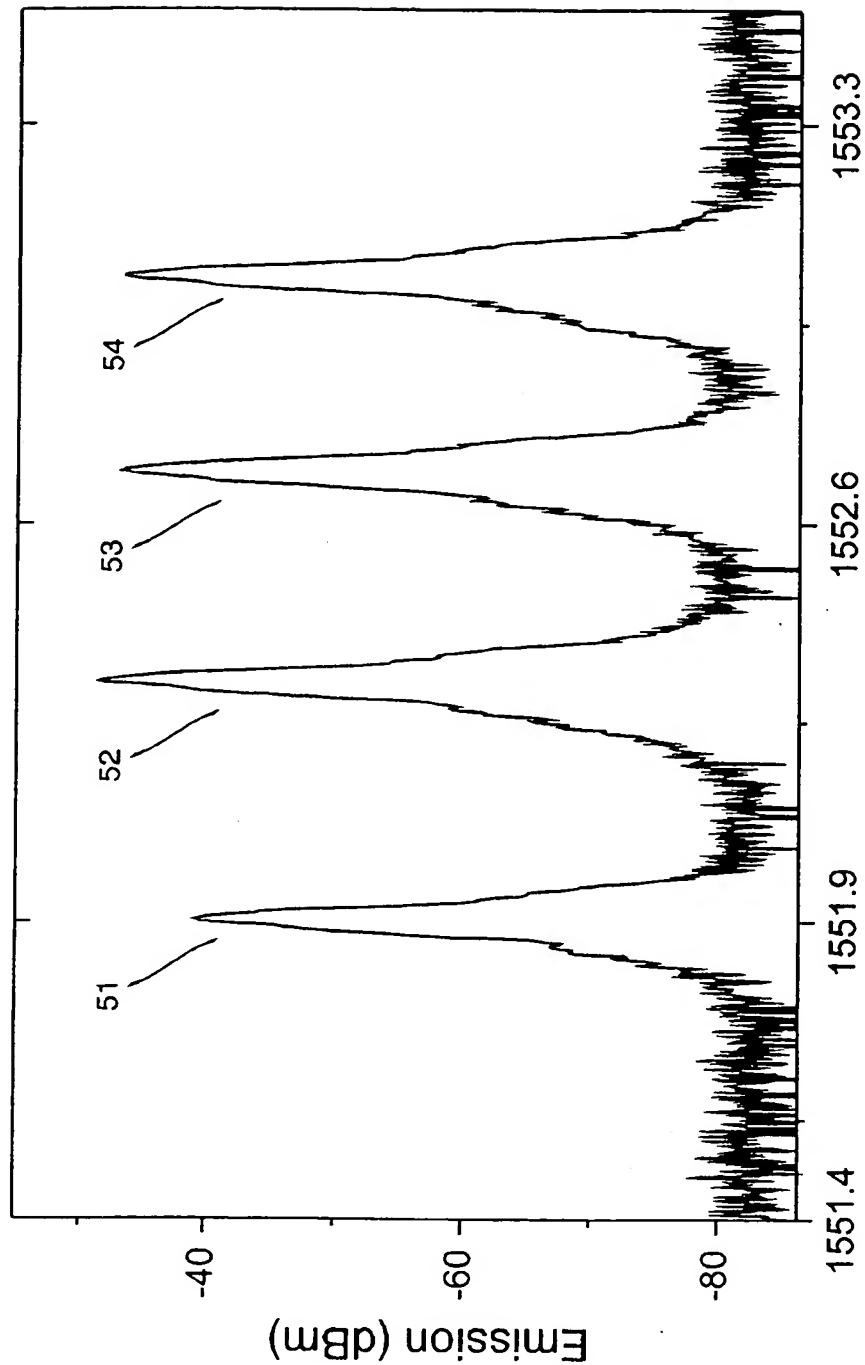
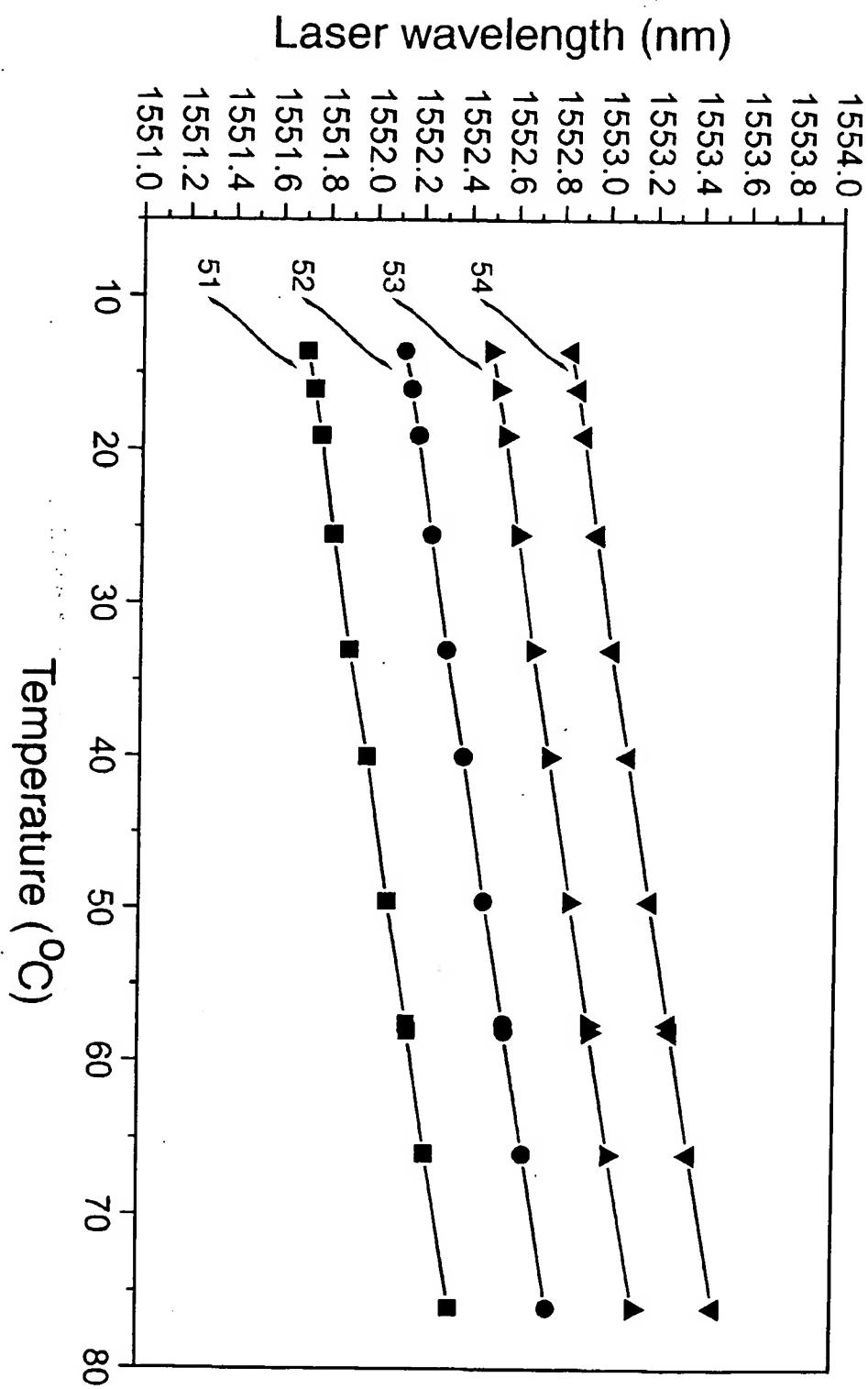


Fig. 4  
Wavelength (nm)

Fig. 5



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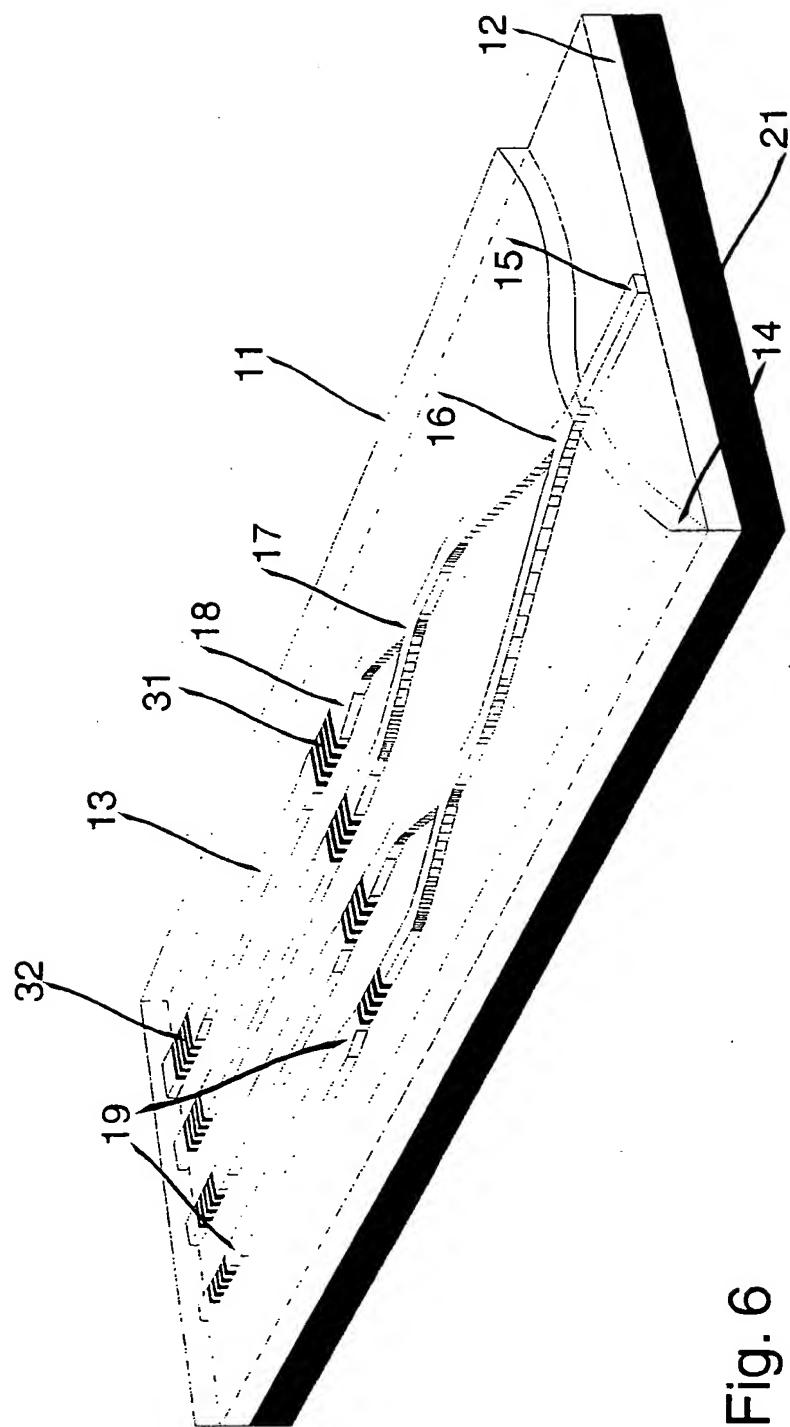


Fig. 6

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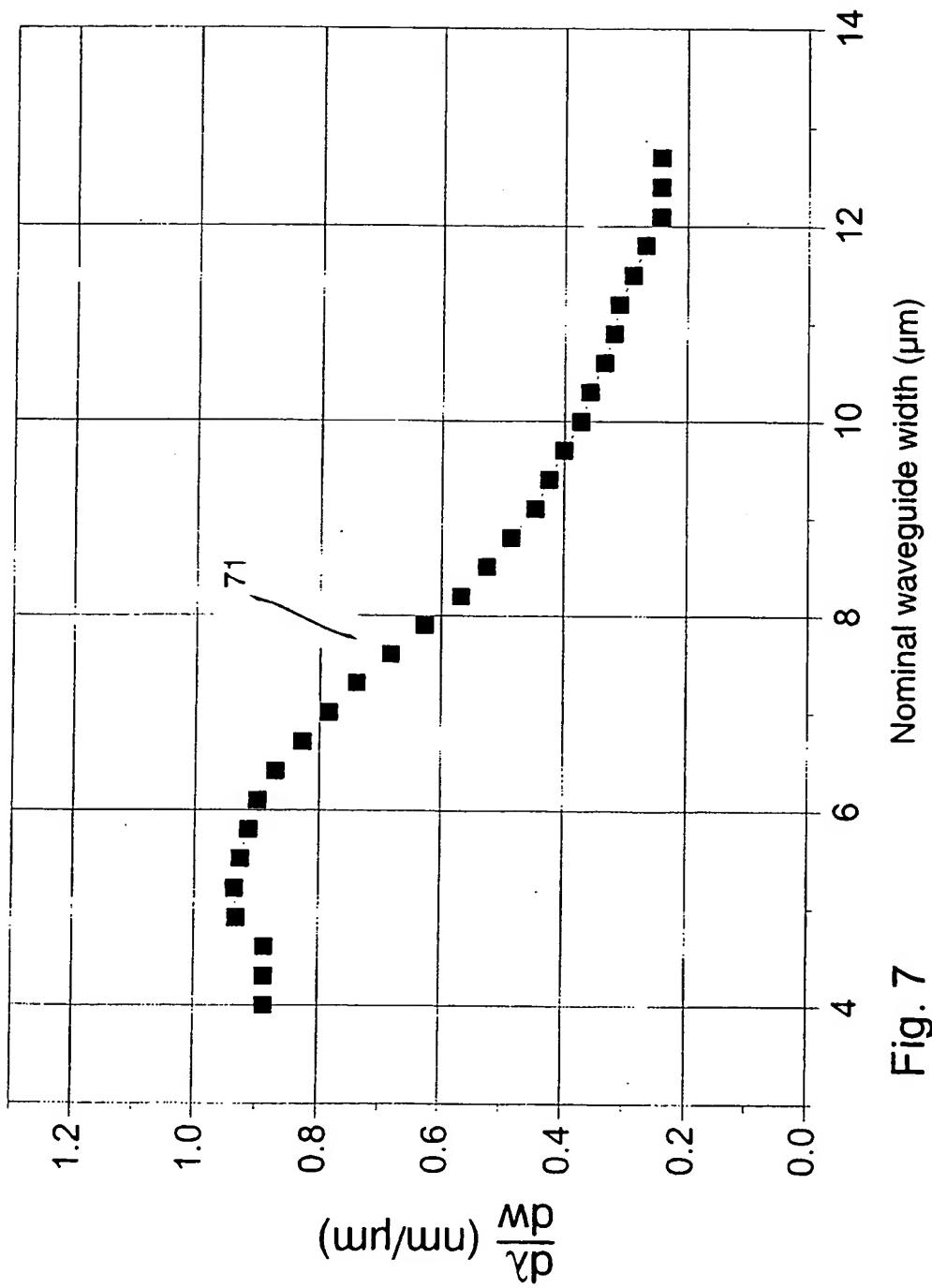


Fig. 7

Nominal waveguide width ( $\mu\text{m}$ )

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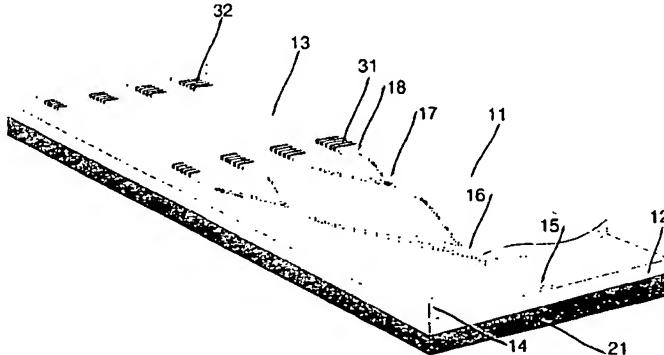
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(54) Title: MULTI-WAVELENGTH LASER SYSTEM



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(57) Abstract: The present invention relates to a system and a method providing multi-wavelength emitting optical integrated planar waveguide device with large wavelength span, having tight control over absolute and especially relative positions of the emitted wavelengths, as well as narrow line widths. The  $n_{eff}$  experienced by a laser mode in a waveguide is at least partly determined by the physical overlap, the confinement factor, between the laser mode and the refractive index profile of the waveguide core. If the waveguides have well defined refractive index profiles, adjusting the transverse dimensions of the waveguide core adjusts the refractive index profile, and thus the confinement factor and  $n_{eff}$ . According to the present invention, two or more waveguide lasers are formed wherein the reflective members forming the laser cavity have a spectrally dependent reflectivity which depends upon the effective refractive index,  $n_{eff}$ , experienced by a laser mode at the position of the reflective member. By identical reflective members, such as Bragg gratings, for the different lasers, the wavelength of the lasers can be adjusted by adjusting the relative transverse dimensions, such as the widths, of the lasers. This allows for a precise relative tuning of the lasers, and eliminates uncertainties in the relative grating periods of the Bragg gratings. The dependence of  $n_{eff}$  upon the width  $w$ ,  $n_{eff}(w)$ , are preferably large in order to span a large range of wavelength using only a small variation in the width of the waveguides. Thereby different lasers will have approximately the same dimensions.

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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/DK 00/00521

**A. CLASSIFICATION OF SUBJECT MATTER**  
**IPC 7 H01S3/23 H01S3/1055 H01S3/063**

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)  
**IPC 7 H01S**

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

PAJ

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category * | Citation of document, with indication, where appropriate, of the relevant passages  | Relevant to claim No.                |
|------------|---|--------------------------------------|
| X          | SASAKI T ET AL: "10 wavelength MQW-DBR lasers fabricated by selective MOVPE growth"<br>ELECTRONICS LETTERS,<br>vol. 30, no. 10, 12 May 1994 (1994-05-12),<br>pages 785-786, XP002901495<br>the whole document | 1-6,13,<br>14,16,<br>17,23,<br>25,26 |
| Y          | ---   | 7-12,15,<br>18-21,24                 |

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

\* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document but published on or after the international filing date
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- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search

19 January 2001

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17.05.01

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## INTERNATIONAL SEARCH REPORT

International Application No

PCT/JP 00/00521

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category * | Citation of document, with indication, where appropriate, of the relevant passages  | Relevant to claim No. |
|------------|---|-----------------------|
| Y          | VEASEY D K ET AL: "Arrays of distributed-Bragg-reflector waveguide lasers at 1536 nm in Yb/Er codoped phosphate glass"<br>APPLIED PHYSICS LETTERS,<br>vol. 74, no. 6,<br>8 February 1999 (1999-02-08), pages<br>789-790, XP002901496<br>the whole document<br>---                         | 1-26                  |
| Y          | PATENT ABSTRACTS OF JAPAN<br>vol. 1998, no. 14,<br>31 December 1998 (1998-12-31)<br>& JP 10 242591 A (NIPPON TELEGR TELEPH CORP), 11 September 1998 (1998-09-11)<br>abstract<br>---   | 1-26                  |
| A          | KITAGAWA T ET AL: "Single-frequency Er <sup>3+</sup> -doped silica-based planar waveguide laser with integrated photo-imprinted Bragg reflectors"<br>ELECTRONICS LETTERS,<br>vol. 30, no. 16,<br>4 August 1994 (1994-08-04), pages<br>1311-1312, XP002901497<br>the whole document<br>--- | 16-24                 |
| A          | TALNEAU A ET AL: "Agile and fast switching monolithically integrated four wavelength selectable source at 1.55μm"<br>IEEE PHOTONICS TECHNOLOGY LETTERS,<br>vol. 11, no. 1, January 1999 (1999-01),<br>pages 12-14, XP002901498<br>the whole document<br>-----                             | 1-15                  |

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/DK 00/00521

### Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1.  Claims Nos.: because they relate to subject matter not required to be searched by this Authority, namely:
  
2.  Claims Nos.: because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
  
3.  Claims Nos.: because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

### Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1.  As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
  
2.  As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
  
3.  As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
  
4.  No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-25

Remark on Protest

The additional search fees were accompanied by the applicant's protest.  
 No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-25

The invention according to claim 1-15 relates to a laser system with two waveguide lasers, each with two reflecting members. The laser mode in the first laser experiences a first effective refractive index  $n_{eff}$  at one of the refractive members, where the waveguide has a width  $w$ . The laser mode in the second laser experiences a second refractive index at one of the refractive members, where the waveguide has another width and effective refracting index than the first laser. The dependence between the effective refractive index and the width at the reflective members shall satisfy  $d_{neff}/dw > 2 \times 10^{-4} \mu\text{m}^{-1}$  for both lasers.

The invention according to claim 16-25 relates to a single waveguide laser with two reflective members and a centre wavelength  $\lambda$ , where the core width  $w$  of the waveguide, at the position of the first reflective member, shall satisfy  $d/\lambda w < 0.2 \text{ nm}/\mu\text{m}$ .

2. Claims: 26-34

The invention according to claim 26-34 relates to a method of fabricating a laser with a core and cladding region and with a reflective member at each end. The core width at one end is adjusted to obtain a specific wavelength.

**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International Application No

PCT/UK 00/00521

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|--|------------------|-------------------------|------------------|
| JP 10242591 A                          | 11-09-1998       | NONE                    |                  |